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Title: Beam Stability Overview

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Beam Stability Overview

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December 13, 2021

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In this talk I will try to answer a few questions that you might have:

- **Why we are doing this.**
- **What we are doing.**
- **How we are doing it.**
- **What the results are to date.**

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Radiographic spot size is affected by many factors, including beam motion due to instabilities.

- **Even low-level instability motion can seriously affect radiography.**
  - **High-frequency beam motion can blur the radiographic source spot.**
  - **Low-frequency beam motion can cause spot-to-spot wander.**

- **Emittance growth can result from instability, as well as other effects**
  - **Parametric halo production by mismatched-envelope oscillations**
  - **Edge focusing by spherical aberration of solenoids**

- **The magnetic tune of the beam-transport solenoids has a profound effect on beam motion.**
  - **Many high current instabilities are suppressed by the magnetic field.**
  - **Some sources of motion are enhanced by the magnetic field.**

Instabilities and effects that can influence the radiation-source spot size are being evaluated for the Scorpius flash-radiography accelerator.

- Many concerns were evaluated for early, conventionally-powered designs (72 cells).
- Progress of evaluation can be summarized by the following chart:

Physical Effect	Transport B-Field Impact		Analytic Theory	Simulation Status		Related Publications
	Suppress	Enhance		72 Cells	102 Cells	
Beam Breakup	X		Done	Done	Done	D1, D2, A, S
Image Displacement	X		Done			D1
Ion-Hose	X		Done	Done	In Progress	D2, A
Resistive Wall	X		Done	Done	In Progress	A
Diochotron	X		Some		In Progress	
Parametric Envelope		X	Done	Done	Done	S
Corkscrew		X	Done	Done	Done	D2, S
Mismatched Halo		X	Done	Done	In Progress	D2, S
Chromatic Aberration			Done			
Spherical Aberration			Done	Done		D2

D1=DARHT-I, D2=DARHT-II, A=ARIA, S=Scorpius

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The Scorpius LIA design has a direct influence on beam stability. Many features of the design were specifically incorporated to mitigate instability.

- 102 cells, grouped in modules of 3 and blocks of 12, with 200 kV/cell.
- Nominal tune has less than 1.5 kG magnetic field on axis.
- Nominal tune phase-advance/cell is less than π.
- DARHT-I gap and insulator design incorporated to mitigate BBU.
- Ferrite damping rings incorporated to mitigate BBU
- Solenoids are capable of up to 2.0 kG on axis for BBU suppression
- Greater than 220-kV/m average gradient
- Vacuum pumping distributed between cells to minimize ion-hose instability.
- High conductivity beam pipe in DST to minimize resistive-wall instability.

The major beam dynamics concerns for high-current LIAs are being evaluated for the long, 102-cell Scorpius design.

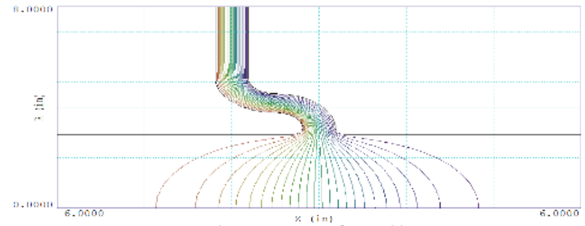
- **The Scorpius LIA design is more than twice as long, has 50% more cells, and 50% stronger magnetic fields than DARHT-II, so it is necessary to evaluate how this substantial increase in proportions affects beam stability.**

- **In order to complete a consistent analysis of the most dangerous instabilities and effects in a timely fashion, the lattice dimensions were "frozen" in November, 2020.**
  - **The accelerator simulations and tuning used the lattice provided by Juan Barraza on 9/29/20.**
  - **External electromagnetic fields were derived from simulations based on engineering drawings as of November, 2020.**

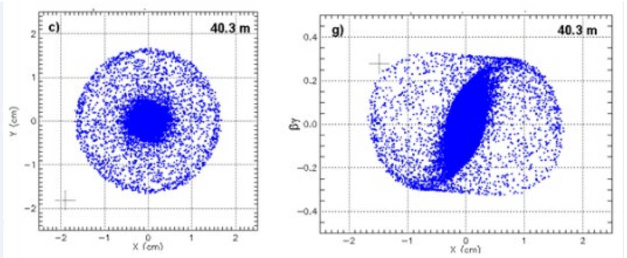
- **Although there have been some minor changes in locations of elements since then, they are not expected to change the conclusions of this study.**
  - **Modules have been rearranged**
  - **Inter-gap spacing changed by < 1 cm**
  - **LIA length has grown by ~23 cm**

For the results that I will share today, I used all of the tools at our disposal.

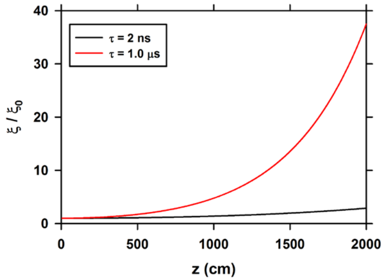
- Experimental Data
- Analytic Theory
- Physics Simulation Codes
  - Electromagnetics (Estat, PerMag, POISSON)
  - Beam dynamics codes (XTR, LAMDA, TRAK)
  - Particle-in-cell (PIC) codes (LSP)



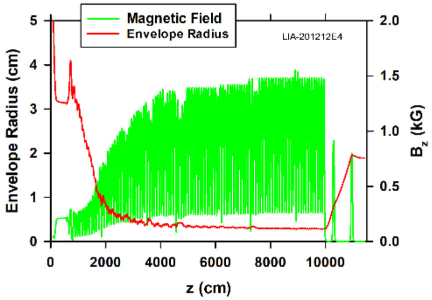
Estat simulation of cell-gap potential



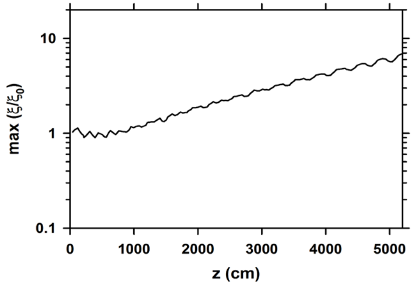
LSP PIC simulation of beam halo



LAMDA simulation of Resistive-Wall



XTR simulation of matched transport



LAMDA simulation of BBU growth

"Cathode to Target Simulations for Scorpius: I. Simulation Codes and Models," C. Ekdahl, LA-UR-21-21022, and arXiv:2104.14593, 2021

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In the time remaining, I will share some of the results to date of these analyses and simulations.

Physical Effect	Transport B-Field Impact		Analytic Theory	Simulation Status		Related Publications
	Suppress	Enhance		72 Cells	102 Cells	
Beam Breakup	X		Done	Done	Done	D1, D2, A, S
Image Displacement	X		Done			D1
Ion-Hose	X		Done	Done	In Progress	D2, A
Resistive Wall	X		Done	Done	In Progress	A
Diochotron	X		Some		In Progress	
Parametric Envelope		X	Done	Done	Done	S
Corkscrew		X	Done	Done	Done	D2, S
Mismatched Halo		X	Done	Done	In Progress	D2, S
Chromatic Aberration			Done			
Spherical Aberration			Done	Done		D2

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Injected Beam;

Initial Conditions for Transport through the LIA

For this evaluation, the initial conditions for transport and acceleration of the beam through the LIA were provided by an early design of the injector.

- Hot dispenser-cathode electron source
- Push-pull IVAs produce 2.0 MV across diode with 1:1 ratio.
  - 1.0 MV from negative IVA
  - 1.0 MV from positive IVA
- Diode has both electric and magnetic focusing
  - Pierce electrode for electric focusing
  - Anode solenoid for magnetic focusing
- Shielded diode design to produce a beam with zero canonical angular momentum to minimize focal spot.
  - Reversed-field "bucking coil" nulls magnetic flux linking the cathode.
- Space-charge limited current is ~1.5-kA at 2.0 MV.
- Magnetic transport through long anode beam pipe by 36 solenoids in the IVA cells (many loops at large radius ≈ a long solenoid).

Beam production in the 1:1 push-pull diode was simulated by Will Stem (LLNL) using TRAK.

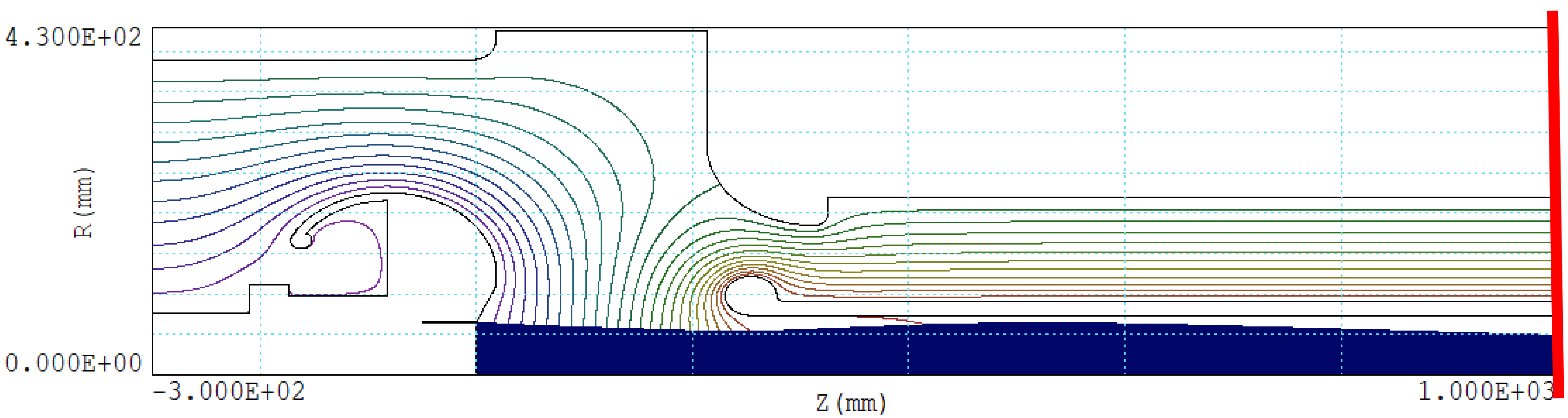
- **Will's design for diode electrodes minimizes the emittance growth due to edge focusing by the nonlinear electric field (spherical aberration).**
- **I changed the magnetic boundary condition to Dirichlet and expanded the calculation region (imperceptible effect on beam).**
  - **This is what I usually use, because the special Neumann condition in PerMag forces an unphysical orthogonal field at boundaries.**
- **I reduced the bucking coil current by about 6% to obtain a better null of canonical angular momentum.**
  - **Four orders of magnitude reduction of the effective normalized Larmor emittance to << 1 mm-mr.**

TRAK simulations showed that a beam with acceptable parameters could be produced by the redesigned diode.

The TRAK beam parameters are handed off to envelope and PIC simulations at a location far enough into the anode pipe that the diode electric fields are insignificant compared with the field of the space-charge dominated beam.

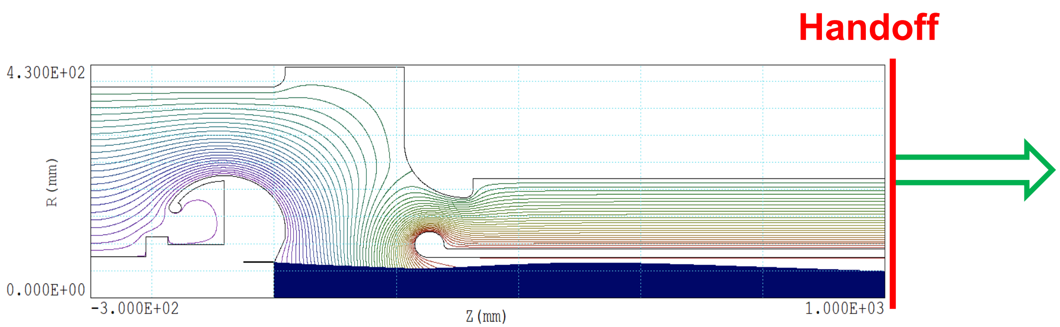
Beam Parameters

- z = 100 cm (handoff)
- KE = 2.0 MeV
- I_{beam} = 1.445 kA
- R_{env} = 5.011 cm
- dR_{env}/dz = -35.24 mr
- ε_n = 203.6 mm-mr

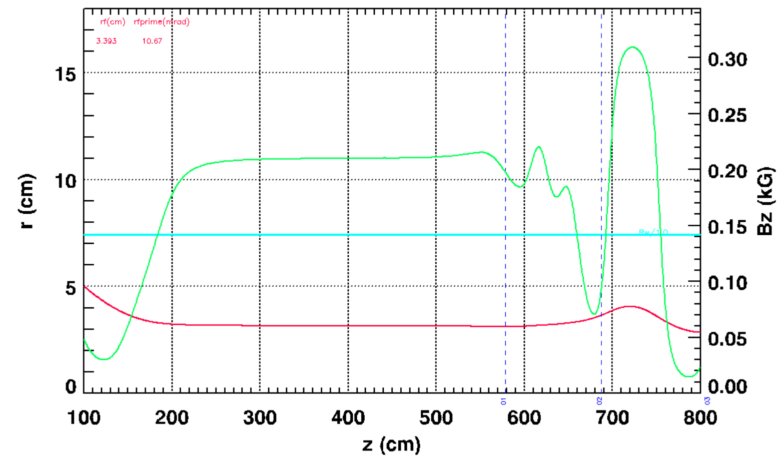


Tuning the injector anode to transport a 3-cm envelope radius beam enables drifting the beam > 1-m after the exit.

Will Stem's early 1:1 Push-Pull Diode Design was used for this evaluation.



Large-diameter, closely-spaced solenoid loops support well-matched beam transport through the 7-m long anode tube.



Beam Parameters from TRAK at 100-cm Handoff

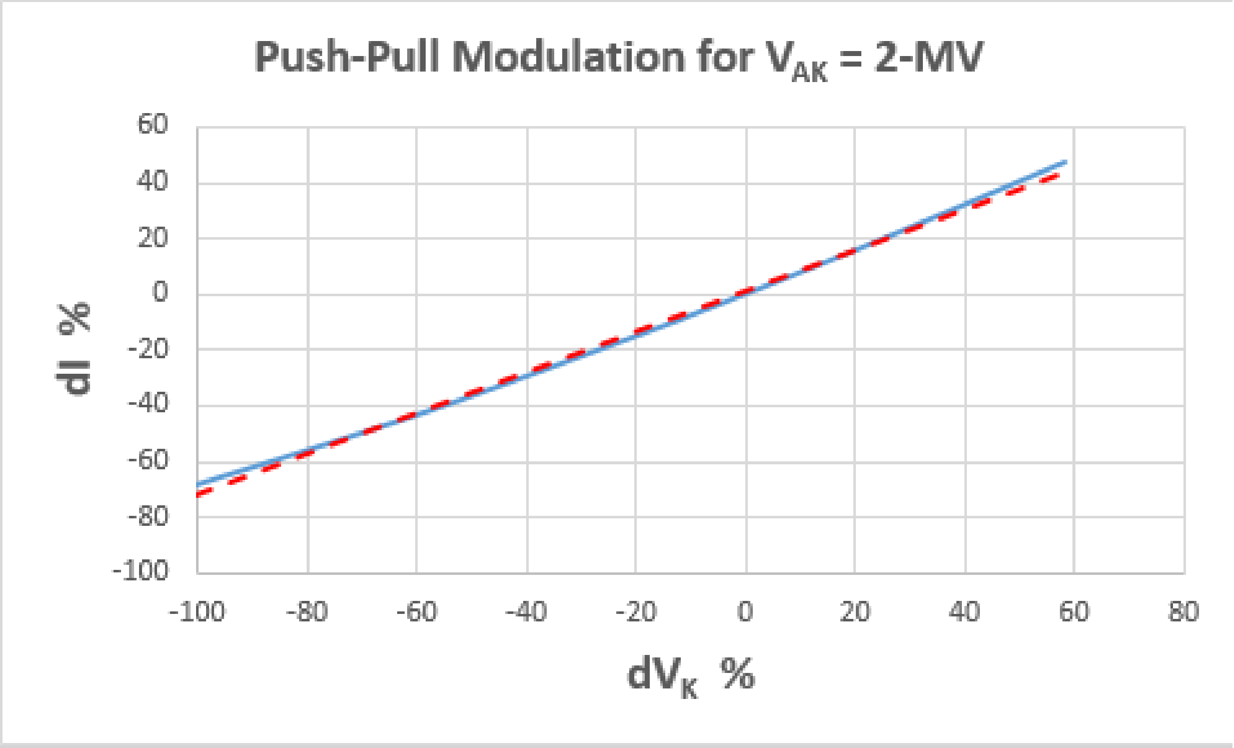
- **KE = 2.0 MeV**
- **I_b = 1.45 kA**
- **ε_n = 204 mm-mr**
- **R_0 = 5.01 cm**
  - **Envelope = 1.414 R_{rms}**
- **R_0' = - 35.2 mr**
  - **Derived from ε_n & R_0**

Design Principles for Anode Transport of a 2-MeV, 1.45 kA beam:

- **Maximum drift to next section ≈ 40 R_{beam},**
- **R_{beam} = 3 cm gives > 1-m drift possible**
- **3-cm matched beam requires B_z ~ 200 G**

The push-pull injector is essentially a grid-less triode, and the push/pull ratio can be used to modulate the beam current without changing its energy.

- **A change in push-pull ratio causes a corresponding change in beam current, even if the beam energy is unchanged.**
- **The modulation is approximately linear over a wide range.**



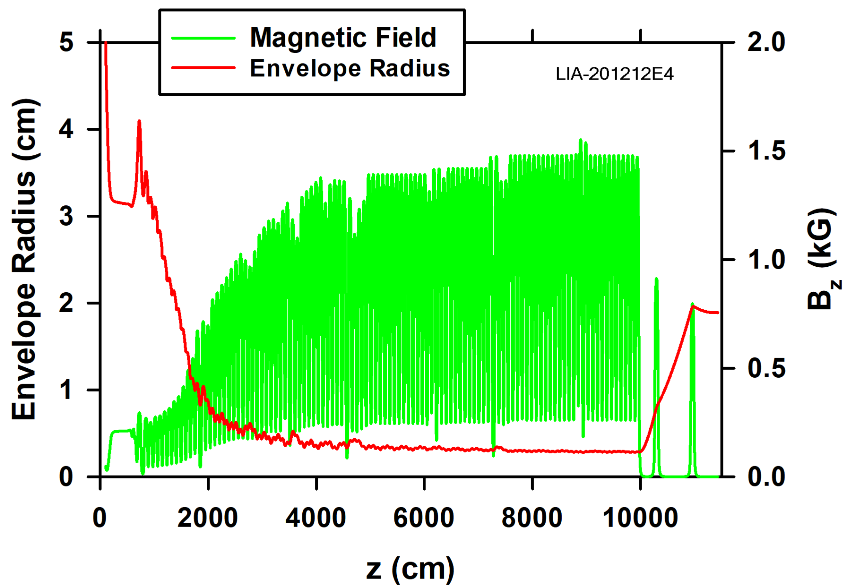
Tuning the LIA for Matched Transport

Stability of the beam in the accelerator is profoundly dependent on the details of the transport magnetic field.

A nominal tune has been designed that shows promise for stable beam transport while it is accelerated through the LIA.

Design Principles for the LIA tune:

- **Limit B-field to meet facility power constraints.**
- **Minimize B-field to defeat phase-advance destabilization of envelope.**
- **Provide sufficient B-field strength to suppress high-current BBU, IDI, Ion-Hose, Resistive-Wall, and Diochotron instabilities.**
- **Rapidly reduce beam size to minimize emittance growth due to spherical aberration of solenoids.**
- **Minimize betatron envelope oscillations that can parametrically pump halo[1].**



The peak B-field is less than 1.5 kG.

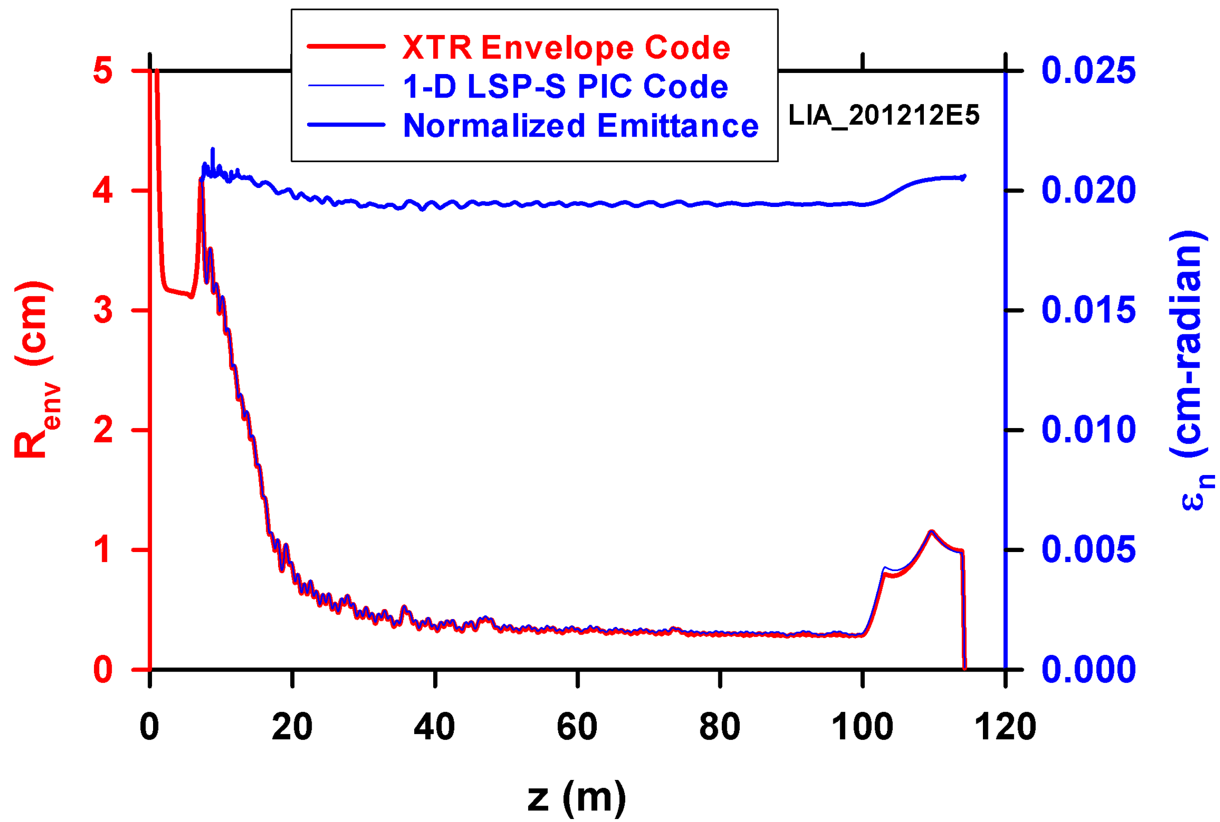
The injected beam is well matched:

- **No large envelope oscillations**

[1] "Emittance Growth in the DARHT-II Linear Induction Accelerator," C. Ekdahl, et al., IEEE Trans. Plasma Sci., vol. 45, Nov., 2017 pp. 2962- 2973

With this nominal tune, the beam envelope has minimal betatron oscillation amplitude and no emittance growth due to halo[1].

- **Faint envelope oscillations evident in PIC code result are too weak to generate large halo that would result in emittance growth.**



[1] "Emittance Growth in the DARHT-II Linear Induction Accelerator," C. Ekdahl, et al., IEEE Trans. Plasma Sci., vol. 45, Nov., 2017 pp. 2962- 2973

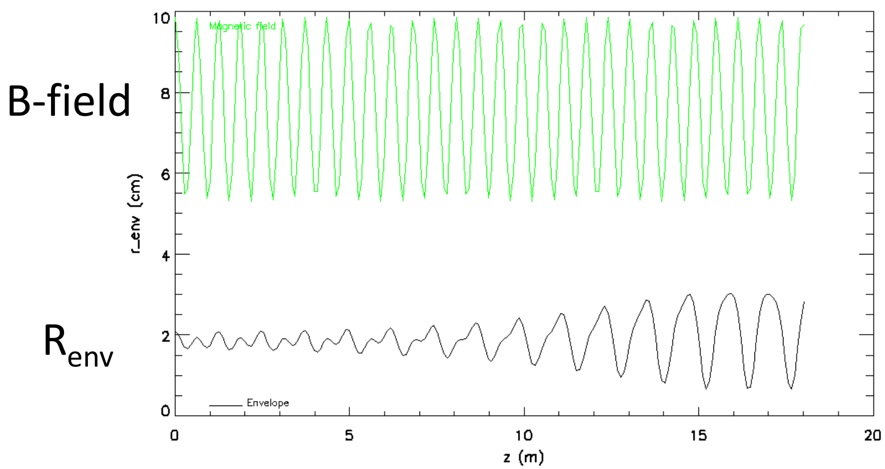
Parametric Envelope Instability
(Lattice Stability)

High-current LIAs with periodic focusing like Scorpius are susceptible to parametric processes that can become unstable.

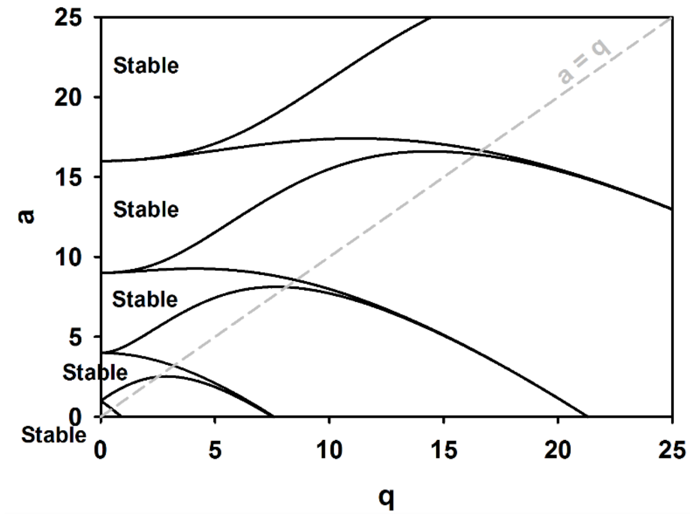
- Parametric processes can often be analyzed by perturbing the harmonic oscillator equation with a periodic potential, thereby getting Mathieu's equation.

$$\frac{d^2 y}{d\theta^2} + \left[a - 2q\cos 2\theta\right] y = 0$$

- This equation describes such classical phenomena as the inverted pendulum, FM radio, and your granddaughter pumping her backyard swing.
- It also describes such phenomena as the image displacement instability (IDI), the parametric envelope instability, and halo growth due to envelope oscillations.
- The solutions have well-known bands of stability/instability.



Parametric instability in envelope code results



Scorpius is susceptible to a parametric envelope instability (PEI), because of its nearly periodic focusing.

- **Established theory proved that single-particle transport through a periodic focusing lattice is only stable if phase advance/cell $\sigma_0 < \pi$.**
  - **Phase advance /cell: $\sigma_0 = \int k_\beta \, dz$**
  - **Betatron wavenumber: $k_\beta = B_z(\text{kG}) / 3.4\beta\gamma$ (/cm)**
- **Envelope instability in periodic focusing discovered in early simulations of low-current beam transport through a periodic lattice led to stability criteria devoid of beam properties, e.g., stability for $\sigma_0 < \pi/2$**
- **Recent theory and simulations for high-current, high-emittance beams suggest more restrictive stability criteria that include beam properties (space-charge, energy, emittance) as well as "vacuum" phase advance of the lattice:**

$$k_s^2 L^2 = \left[\left(1 + c_1 / 2\right) k_{\beta 0}^2 + \frac{K}{r_{m0}^2} + 3\frac{\varepsilon^2}{r_{m0}^4} \right] L^2 < \pi^2$$

"Beam envelope stability in an advanced l in an advanced linear induction accelerator",
C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 49, Oct., 2021, pp 3092-3098

Application of the recent theory shows that the beam envelope is stable to PEI for transport through the Scorpius tune.

Parametric Envelope Instability

(PEI, or Lattice instability)

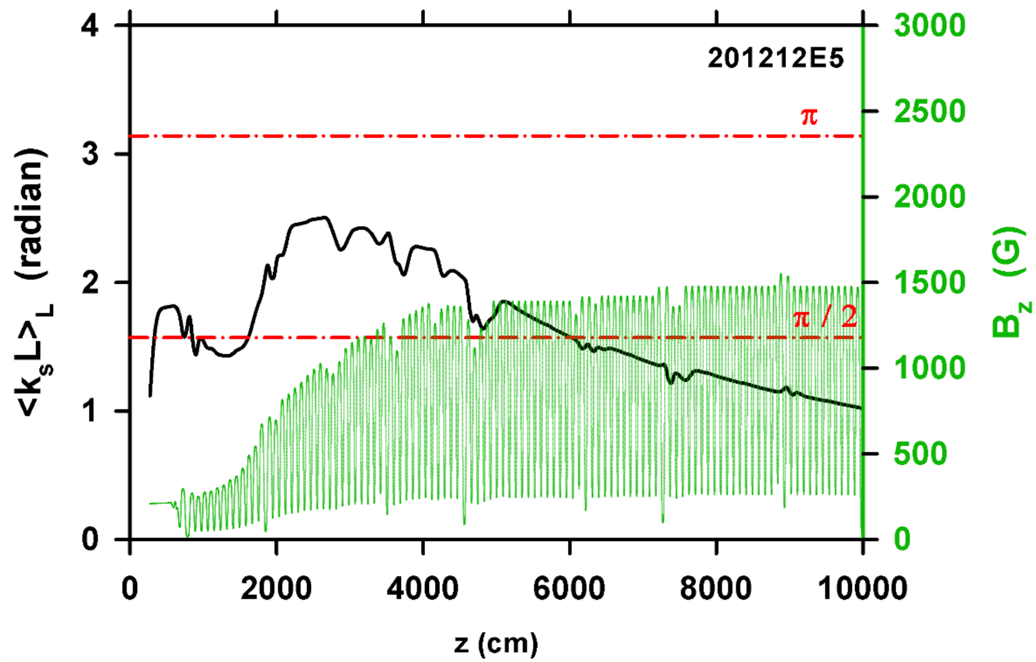
Small perturbations are unstable if $k_sL > \pi$, where

$k_s^2 = (1+c_1/2)k_b^2 + K/r_{m0}^2 + 3e^2/r_{m0}^4$

Unlike earlier criteria, this includes beam parameters, as well as the magnetic lattice.

Since $k_s > k_b$, this is a more restrictive measure of stability than vacuum phase advance, $s_0 = \int k_b dz$

Using a moving average of k_sL over the lattice period L provides a useful measure of tune stability.



The nominal Scorpius tune is stable.

"Beam envelope stability in an advanced l in an advanced linear induction accelerator",
C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 49, Oct., 2021, pp 3092-3098

Engineered Suppression of the Beam Breakup (BBU) Instability

Scorpius is susceptible to beam breakup (BBU) because of its high current and large number of accelerating cavities.

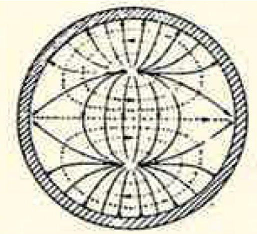
- **BBU: Offset beam excites cavity RF transverse magnetic field modes, which deflect the beam centroid causing RF oscillation of the beam.**
- **The beam pipe is a waveguide beyond cutoff, so cavities only communicate via beam oscillations.**
- **The time to reach maximum amplification,**

$$\tau \propto N_G \langle 1/B_Z \rangle$$

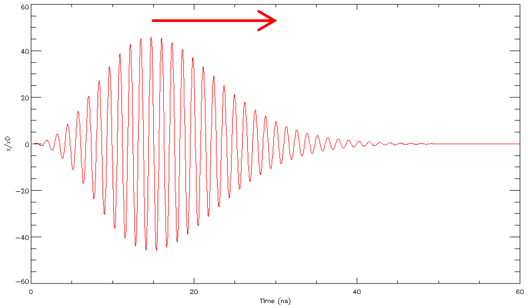
is later for each successive cell (it's convective)

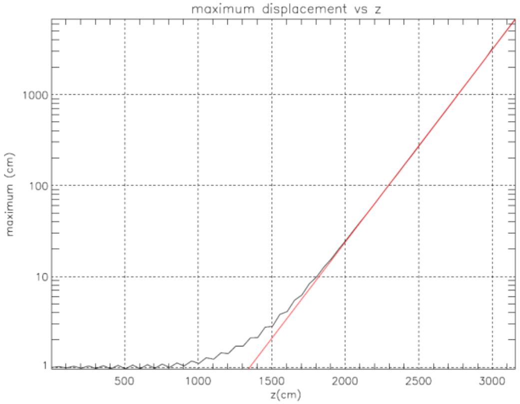
- **Maximum amplification after a large number of cells asymptotes to exponential growth**

$$\boxed{\begin{array}{l} \max(\xi/\xi_0) \propto (\gamma_0/\gamma)^{1/2} e^{\Gamma} \\ \text{where } \Gamma \sim I_b N_G Z_t \langle 1/B_Z \rangle / c \end{array}}$$



TM_{110}





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We have substantially advanced our capability to predict BBU growth in linear induction accelerators like Scorpius.

- ca. 2010 we had good comparisons with theory of results from DARHT [1] experiments and LAMDA simulations [2].
  - The simulations for these comparisons were based on transverse impedance measurements for DARHT-I by Walling, et al.[3], and for DARHT-II by Briggs, et al. [4].
  - However, we had no capability to measure transverse impedance.
  - We offset the risk by basing initial designs for the new LIA on the DARHT-I cell, for which the Walling experimental data and AMOS calculations already existed.

- Rod McCrady has now developed a capability for transverse-impedance measurements of unprecedented accuracy.
  - New measurements of DARHT-I cell agree with the legacy Walling data [5]
  - New measurements agree with CST calculations for several geometries [6,7].
  - Then new measurements of a Scorpius prototype cell have been used to predict BBU growth with the nominal LIA tune [8,9].

Our progress in BBU predictive capability is well documented.

[1] "Long-pulse beam stability experiments on the DARHT-II linear induction accelerator," C. A. Ekdahl, E. O. Abayta, P. Aragon, et al.,*IEEE Trans. Plasma Sci.,* vol. 34, pp. 460-466, 2006.

[2] "Beam Breakup in an advanced linear induction accelerator,“ C. Ekdahl, J. E. Coleman and B. T. McCuistian, *IEEE Tran. Plasma Sci.*, vol. 44, no. 7, pp. 1094 - 1102, 2016.

[3] "Transverse impedance measurements of prototype cavities for a Dual-Axis Radiographic HydroTest (DARHT) facility," L. Walling, P. Allison, M. Burns, et al., in *Proc. 14th Particle Accel. Conf*., San Francisco, CA, USA, 1991.

[4] "Transverse impedance measurements of the DARHT-2 accelerator cell,“ R. Briggs, et al., in *Part. Accel. Conf*., New York, USA, 2001.

[5] "Suppression of beam breakup in linear induction accelerators by stagger tuning," C. Ekdahl and R. McCrady, *IEEE Trans. Plasma Sci.*, vol. 48, no. 10, pp. 3589 - 3599, 2020.

[6] "Transverse Impedance Measurements of the Scorpius Accelerator Test Cell," R. McCrady, Los Alamos National Laboratory report, SCORPIUS-TN-046, 2021.

[7] “Beam coupling impedances of ferrite-loaded cavities: calculations and measurements,” S. Kurennoy and R. McCrady, in *Proc. Int. Part. Accel. Conf.*, 2021

[8] “Beam breakup simulations for the Scorpius flash-radiography accelerator,” C. Ekdahl, S. Kurennoy, R. McCrady, and G. Dale, *IEEE Trans. Plasma Sci.*, vol. , no. , pp. , 2021 (in review)

[9] “Corkscrew excitation of beam breakup in linear induction accelerators,” C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. , no. , pp. , 2022 (in review)

New computational tools for designing BBU-resistant cells have been used for Scorpius. Results have been experimentally validated.

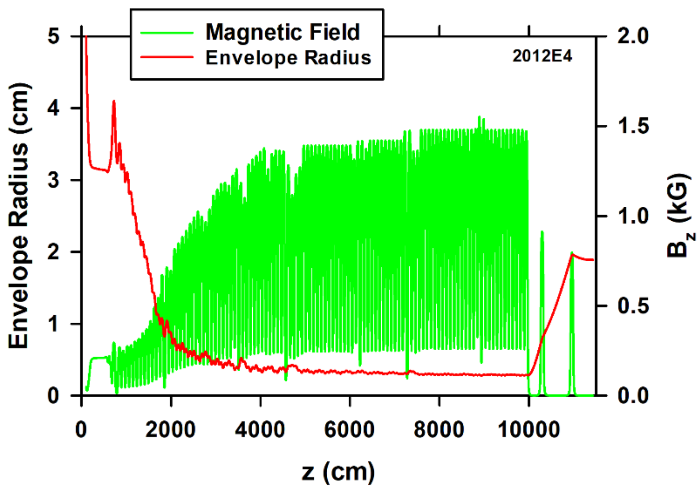
- Sergey Kurennoy is now using two methods in CST calculations of impedance for detailed cell geometries that are based on engineering solid models.
  - Many rapid iterative cycles have led to optimized details, e.g,, damping-ferrite design

- Detailed comparisons with Rod McCrady's measurements have established confidence in this methodology.

- We have exercised our new capability over the past few months to achieve ~30% reduction in impedance from the as-built DARHT-I cells.

- Even with the 60% increase in number of cells for Scorpius, simulations with the LAMDA code predict Scorpius BBU growth less than on DARHT-I, while using magnetic field that is much less than is available for suppression.

Based on impedance measurements and LAMDA simulations, the nominal Scorpius tune is expected to suppress BBU growth to less than in DARHT-I.



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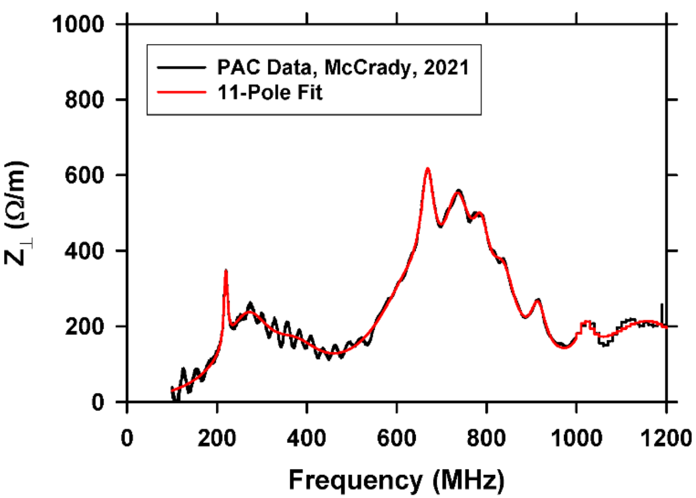

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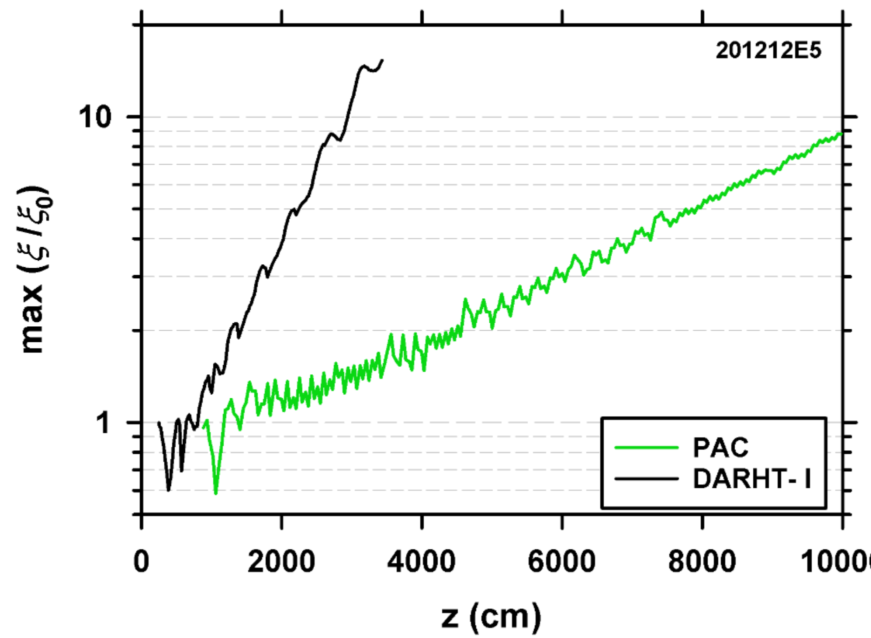
- BBU growth in DARHT-I is reduced by stagger tuning due to asymmetric impedance.
- Scorpius prototype accelerator cell (PAC) has symmetric impedance.



Both simulations were resonantly excited at the peak impedance frequency (worst case).

(in review by TPS)

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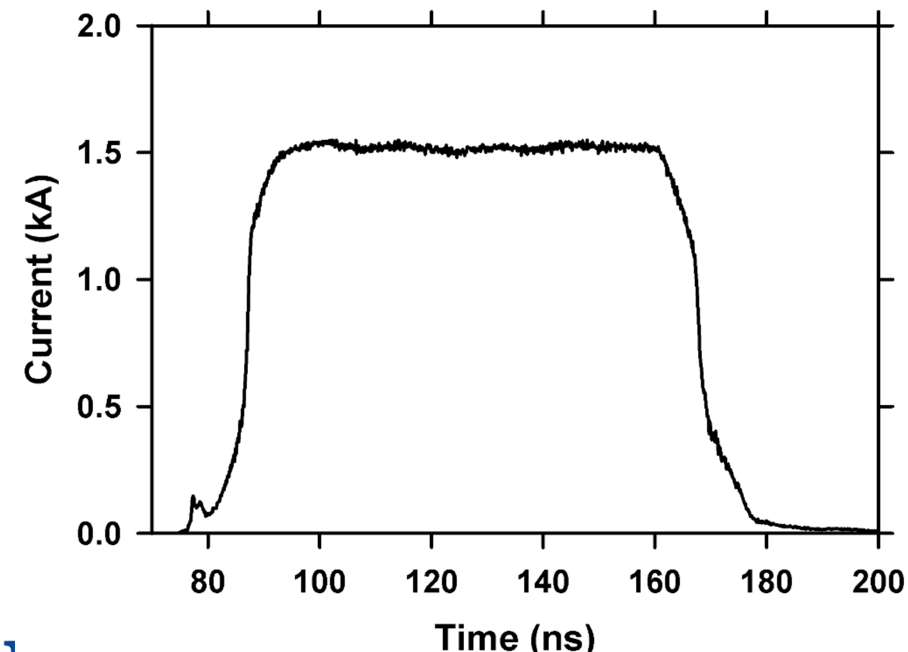
Excitation of the BBU instability by the current-pulse risetime has been simulated using our best estimate of the waveform.

- The current pulse used for these simulations was the result of applying Ray Allen's (NRL) CASTLE simulated IVA voltage to the AK gap of Will Stem's (LLNL) recent (9/20/21) injector geometry.
- Michael Weller (MSTS/NNSS) used LSP (PIC) to simulate the current pulse that was then transported through the long anode, where the off-energy rise-time was sharpened by beam spill.
- This risetime-sharpened pulse was injected into the Scorpius LIA with a 1.0-mm offset to excite BBU.

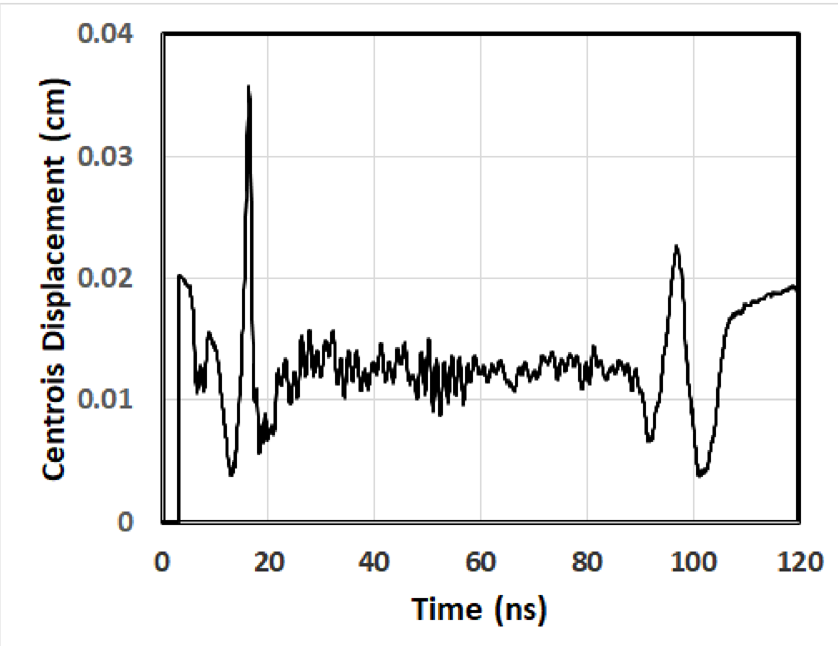


N. B. The 1.52-kA flattop current is slightly mismatched to the LIA tune, which was designed for 1.45 kA.

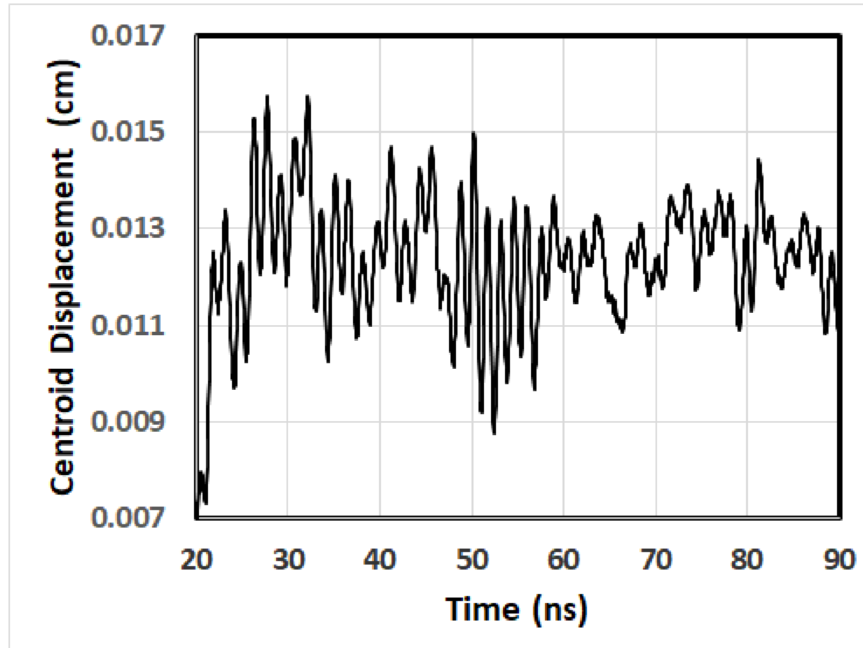
This mismatch causes slight betatron oscillations on the envelope.

Pulse-excited BBU is evident on the flattop at the Scorpius LIA exit.

- The initial 1.0-mm offset is focused down to ~ 0.1 mm by the tune.
- The beam simulations predict a 3-mm envelope radius this location.
- The tune suppresses pulse-excited BBU to < 0.06-mm peak-to-peak.
  - $BBU_{p\text{-}p} < 2\% \ R_{env}$



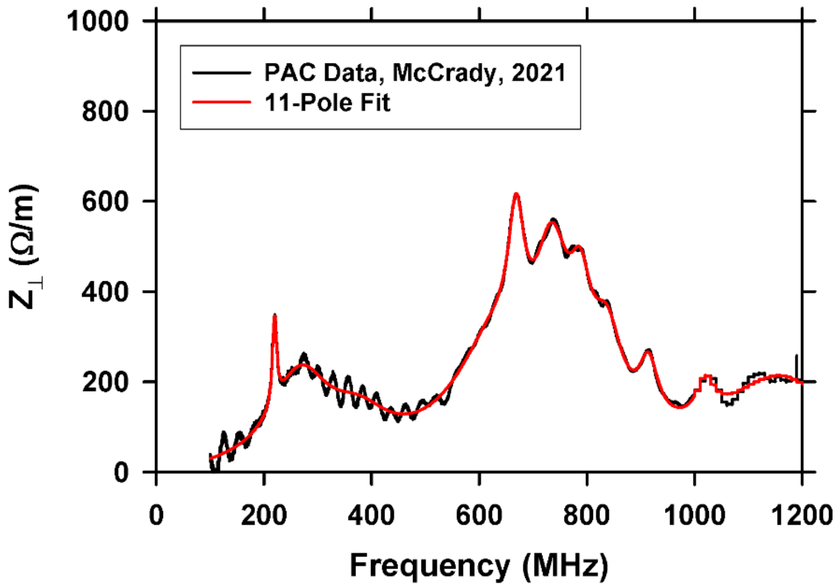
Centroid offset from axis at LIA exit.



(Zoomed) Centroid offset from axis at LIA exit.

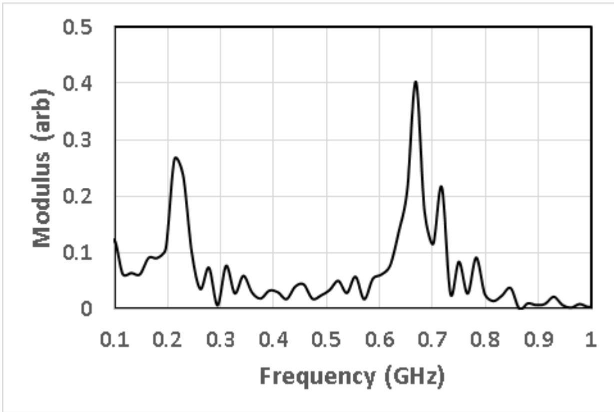
Fourier analysis of the pulse-excited BBU shows activity during the flattop near both major resonances of the cavity.

Measurements of the Scorpius prototype cell indicated strong BBU coupling in two major resonances - ~220 MHz and ~670 MHz.



An FFT of simulation results for the BBU on the flattop showed the same resonance structure as the transverse impedance used for the simulation.

(512 flattop data: 22 ns to 53 ns)



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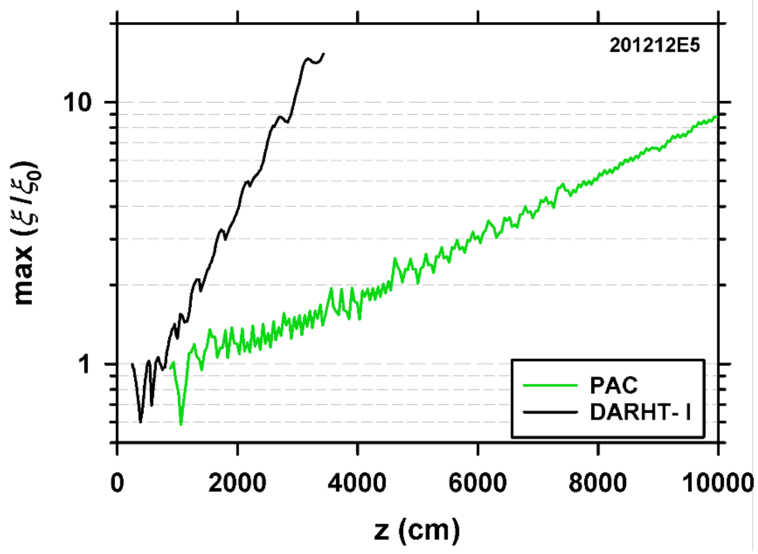
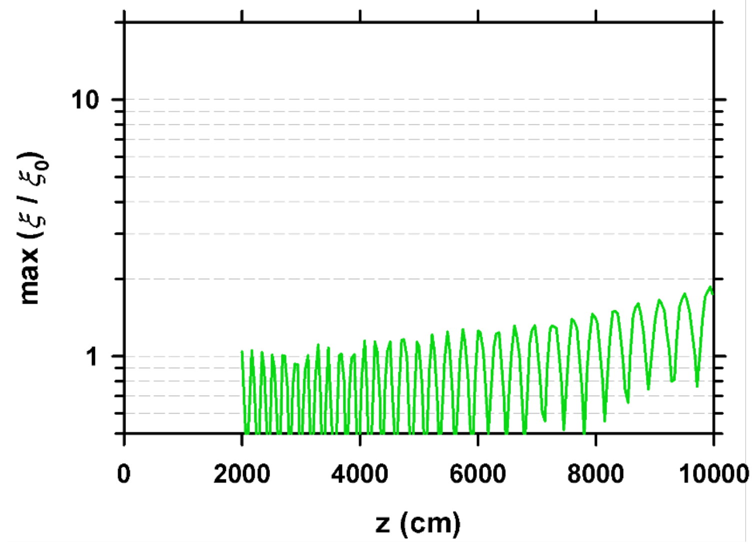
Exponential growth rate of pulse-excited BBU was much less than the growth rate of resonantly-excited BBU.

- **The growth of maximum BBU oscillation displacement from the mean was significantly less for pulse excitation than for worst-case resonant excitation.**
- **Pulse excitation was heavily modulated by betatron oscillations due to the slight mismatch of flattop current to the tune.**



Resonant excitation grew by about a factor of 9.



Pulse excitation only grew by about a factor of 2.

BBU due to other beamline components was estimated from scaling of the resonant excitation results.

- Recall that the number of e-foldings scales as $$\Gamma = \frac{N I_{kA} Z_{\perp \Omega/m}}{3\times 10^4} \left\langle \frac{1}{B_{kG}} \right\rangle$$
  - (The numerical constant is just the speed of light in these practical units.)
- From the simulations; Γ= 2.7 for I_b = 1.45 kA through the 102 cavities with Z = 618 Ω/m, which implies that $\langle 1/B \rangle$ = 0.89 /kG for the nominal magnetic tune.
- The maximum impedances calculated by Sergey Kurennoy with CST were used to estimate number of e-foldings with $\langle 1/B \rangle$ for this tune:

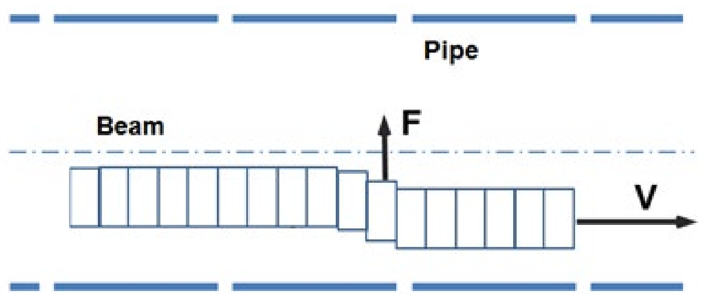
Component	Impedance (Ω/m)	Frequency (MHz)	Number	Scaled e-foldings
Cell Gap and Cavity	618	668	102	**2.71**
Vacuum plenum & grating	144	892	102	**0.63**
Bellows	850	2467	108	**3.95**
Beam Position Monitor	1500	2150	17	**1.10**

Except for the bellows, BBU due to other components is expected to be less than from the cell cavities.

Engineered Reduction of Corkscrew Motion

Scorpius is susceptible to corkscrew motion because of the strong magnetic field needed for BBU suppression.

- **Corkscrew occurs in an accelerator, because segments of beam with different energies are deflected differently by magnetic dipoles that are caused by misalignment of the focusing solenoids.**
- **Theory predicts amplitude dependent on rms misalignment.**
- **Theory also predicts amplitude dependent on the total phase advance:**
  - $\varphi = \int_0^z k_\beta \, dz$ **with** $k_\beta = B_{kG}/3.4\beta\gamma$ **cm^{-1}**
- **Simulated by LAMDA using the Lorentz force deflection of beam segments having different energies.**



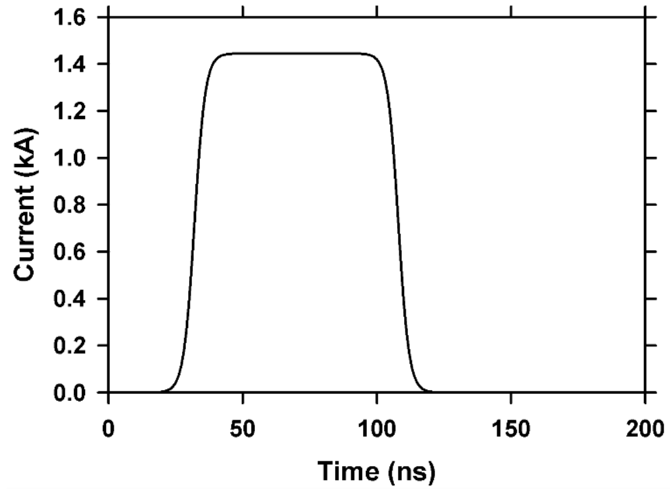
- **High-frequency corkscrew motion can blur the source spot, and it can also seed the BBU.**

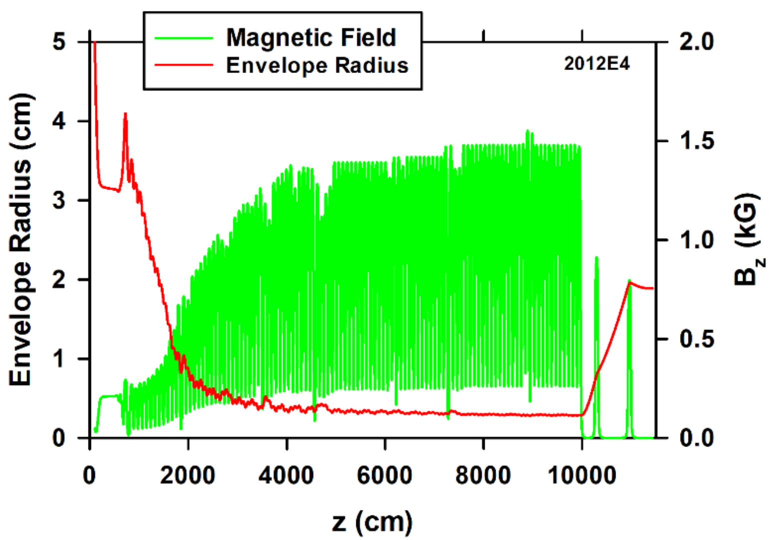
G. Caporaso, et al., "Beam dynamics in the Advanced Test Accelerator (ATA)," in *5th Int. Conf. High Power Charged Particle Beams*, San Francisco, CA, USA, 1982.

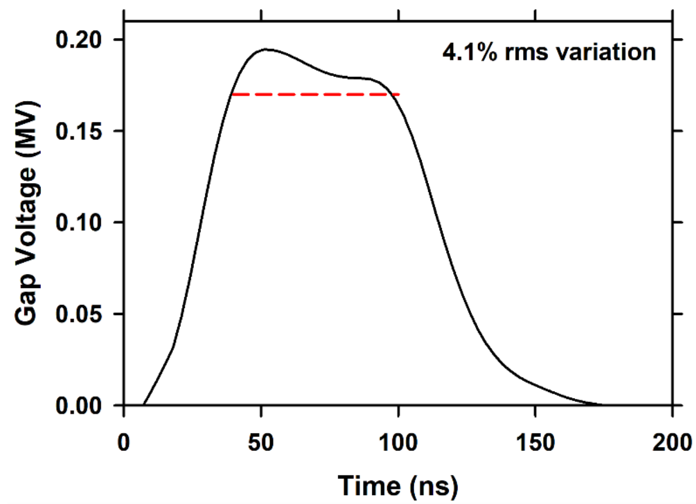
Y.-J. Chen, "Corkscrew modes in linear induction accelerators," *Nucl. Instrum. Methods Phys. Res.*, vol. A292, no. 2, pp. 455 - 464, 1990.

Initial simulations of corkscrew with LAMDA relied on early results of modulated gap voltage simulations.

- Nominal tune that was used for all transport and stability assessments.
- Gap voltage pulse similar to Katherine Velas' (LLNL) early simulations of modulated STAC cell.
- Fast risetime current pulse with 60-ns flattop.
- Solenoid misalignments normally distributed, but truncated to satisfy requirements.
- Corkscrew analyzed during 60-ns current flattop shown by red dashed line.







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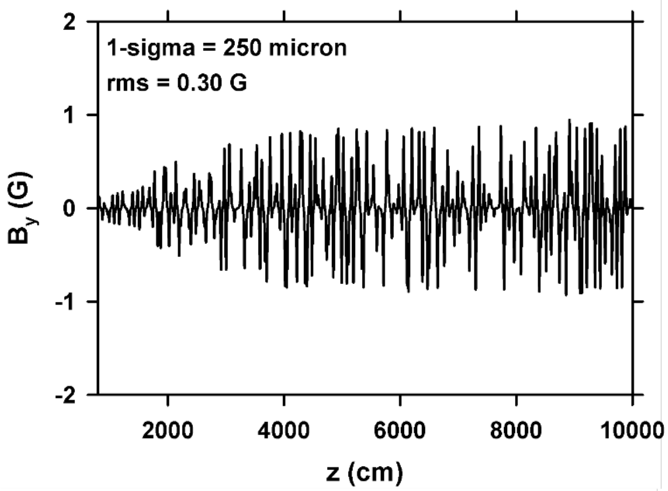
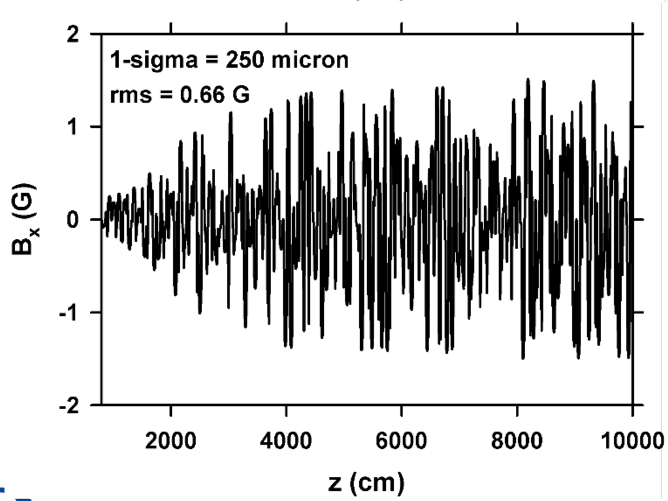
Solenoid misalignments for LAMDA simulations were estimated from requirements and practical statistics.

- **Requirements:**
  - "The tilt of the magnetic axis relative to the mechanical axis of the beam pipe internal surface must be less than 1 mrad."
  - "The offset of the magnetic axis relative to the mechanical axis of the beam pipe internal surface must be less than 0.25mm."
- **Requirements necessitate truncated normal distributions of the expected as-built alignment errors.**
  - Offset error distribution was truncated at 250 microns.
  - Tilt error distribution was truncated at 1milliradian.
- **Practical considerations will drive actual statistics in order to meet requirements**
  - Truncation at 1-sigma => only 68.6% of installed solenoids initially meet requirements (a worst case of poor alignment).
  - Truncation at 3-sigma => 99.6% of installed solenoids meet requirements.
- **Both cases were simulated with LAMDA to demonstrate the improved performance resulting from strict adherence to alignment requirements.**

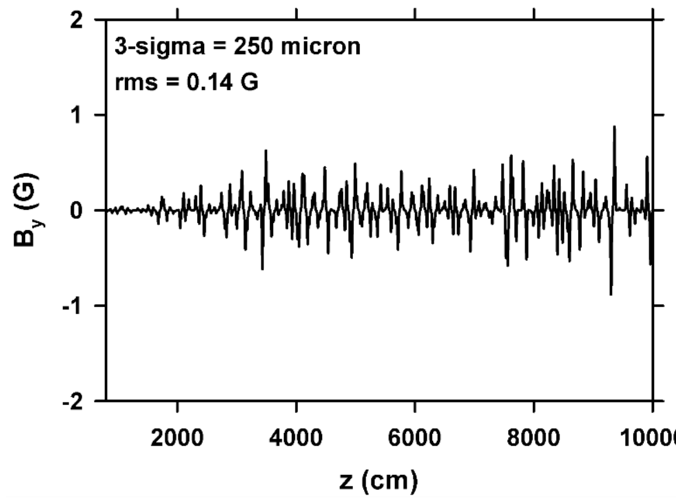
The rms field variation for the case truncated at 3-sigma was about 40% less than for the 1-sigma case.

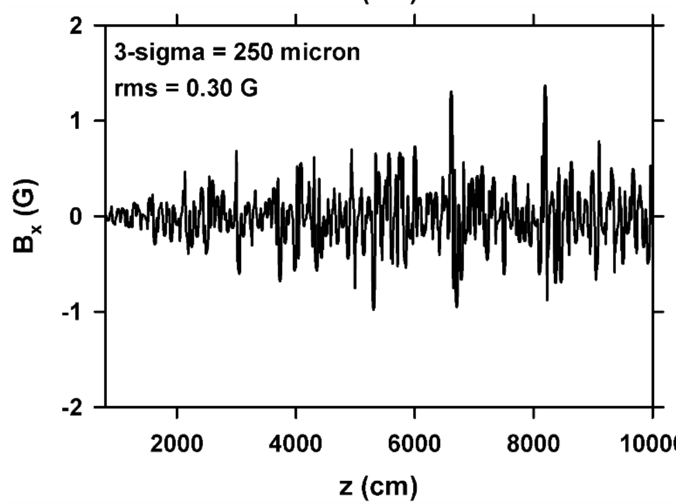
1-σ Truncated Misalignment Fields (Poor Alignment)





3-σ Truncated Misalignment Fields (Good Alignment)





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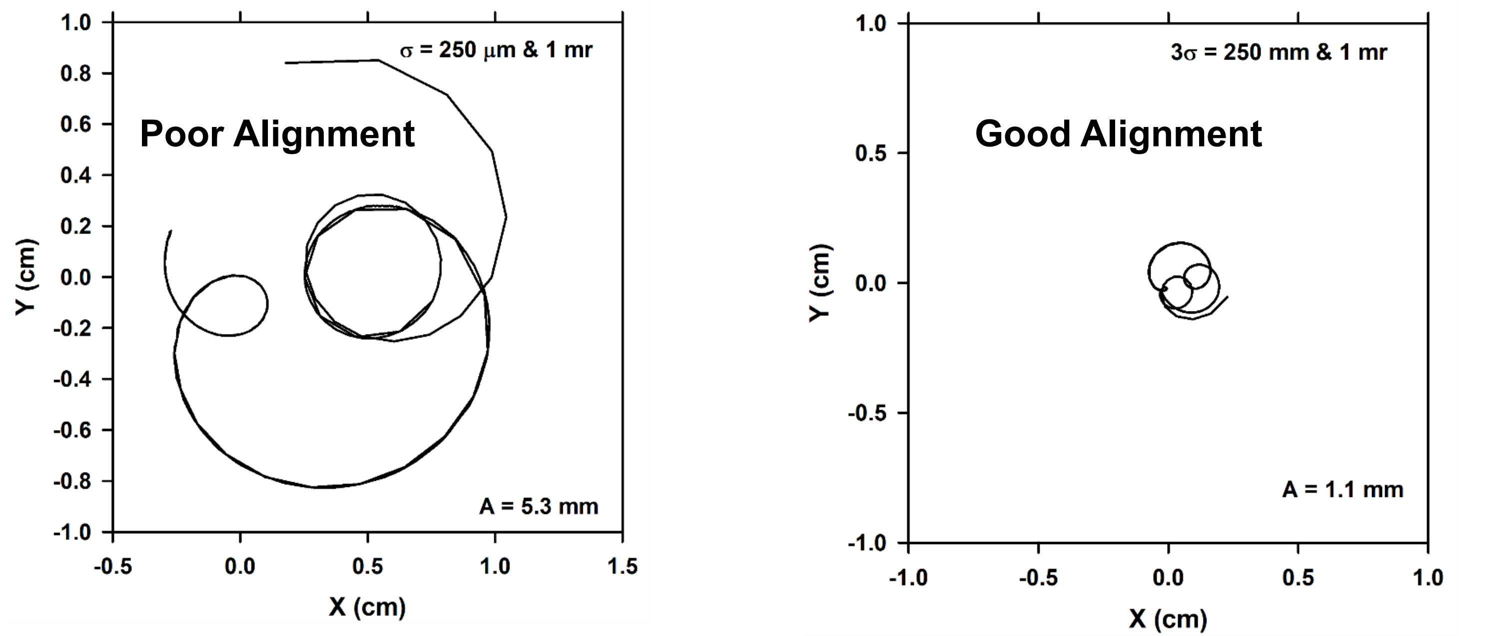
Corkscrew simulations showed the characteristic saturation identified in CDR simulations.

- Corkscrew due to the modulated pulse waveform traces gyro-orbit enclosing flux tubes.
  - Rather than the random walk observed for a random voltage variation.
- Alignment statistics and requirements have a significant influence on saturated amplitude.
- Saturated amplitudes are within range that has been suppressed on DARHT with dipole steering.
  - Simulations used the worst case: Similar to pulse #4 with about 4% rms voltage variation



“Electron-beam corkscrew motion in an advanced linear induction accelerator”, C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 49, Nov., 2021, pp 3548-3553

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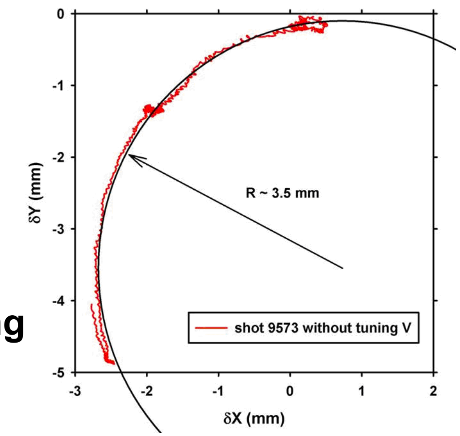
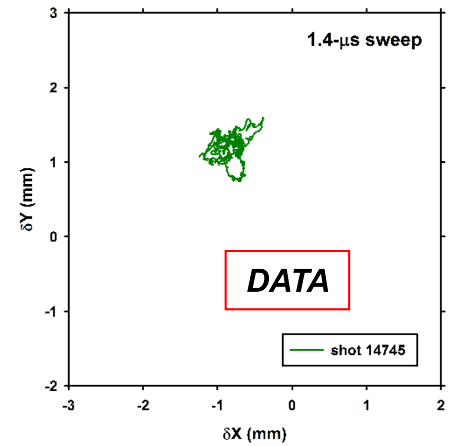
The predicted Scorpius corkscrew amplitude is less than the amplitude that was successfully suppressed on DARHT-II with steering dipoles.

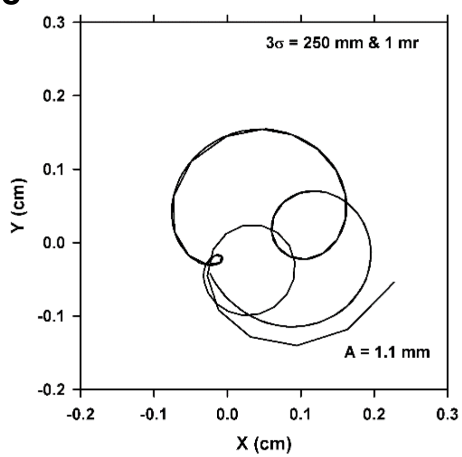
- **Initial DARHT-II corkscrew amplitude was large and unsaturated.**
- **Using the "tuning V" algorithm with steering dipoles reduced it to less than 1 mm.**
- **It is expected that the same algorithm will be just as effective on Scorpius.**

"Tuning V" using Steering Dipoles



DARHT-II





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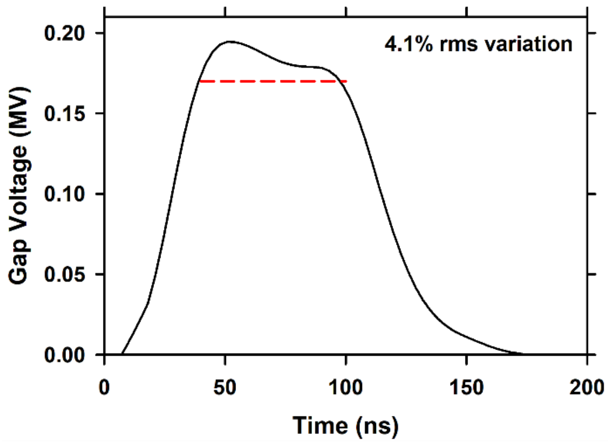
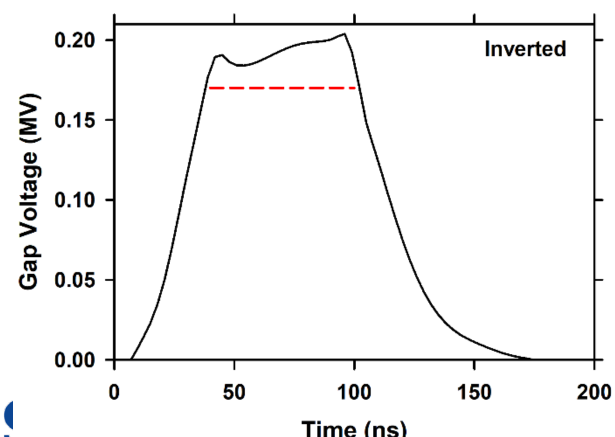
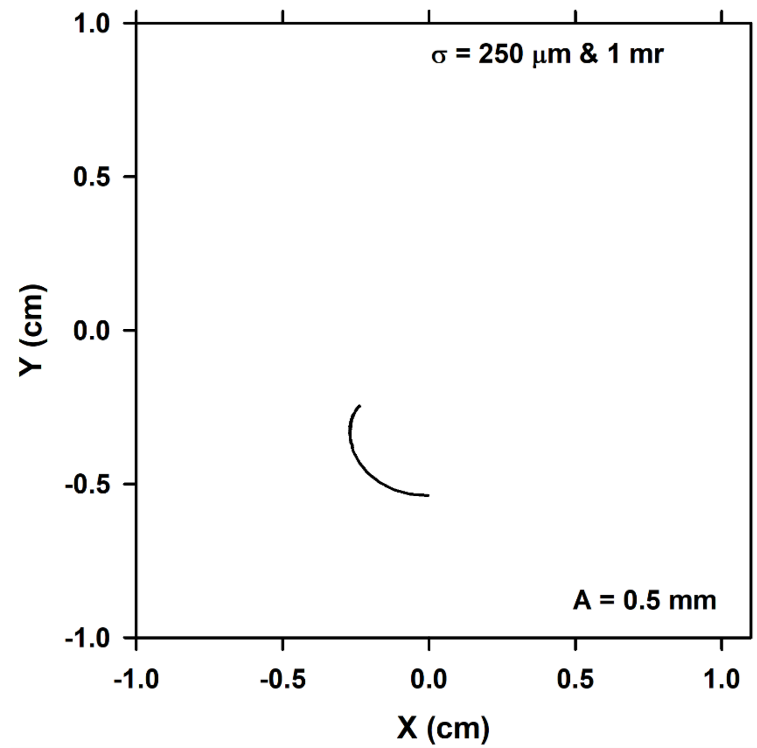
Alternating modulation on adjacent cells can minimize chromatic effects like corkscrew motion, even for worst case scenarios.





This technique can reduce individual 5% cell variations to < 1.5% variation at final focus.

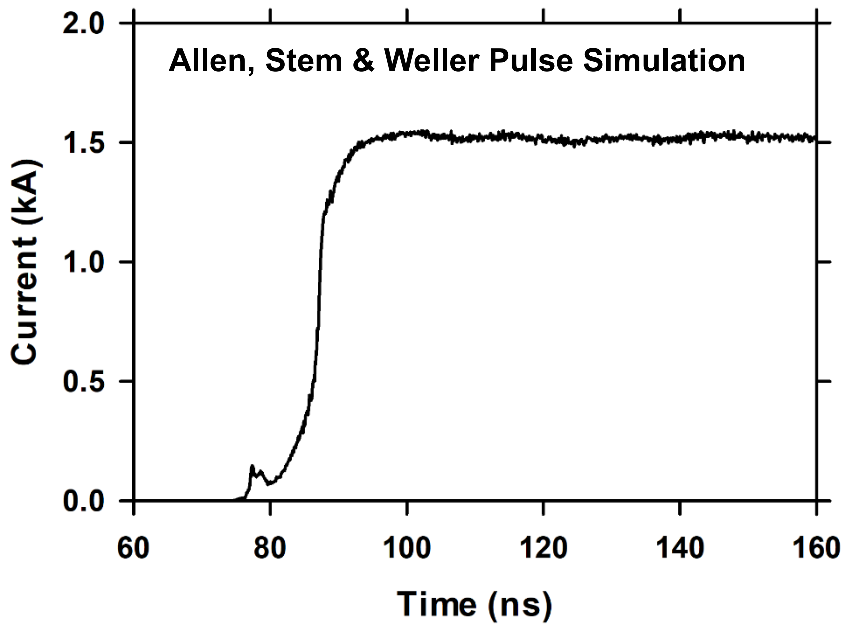


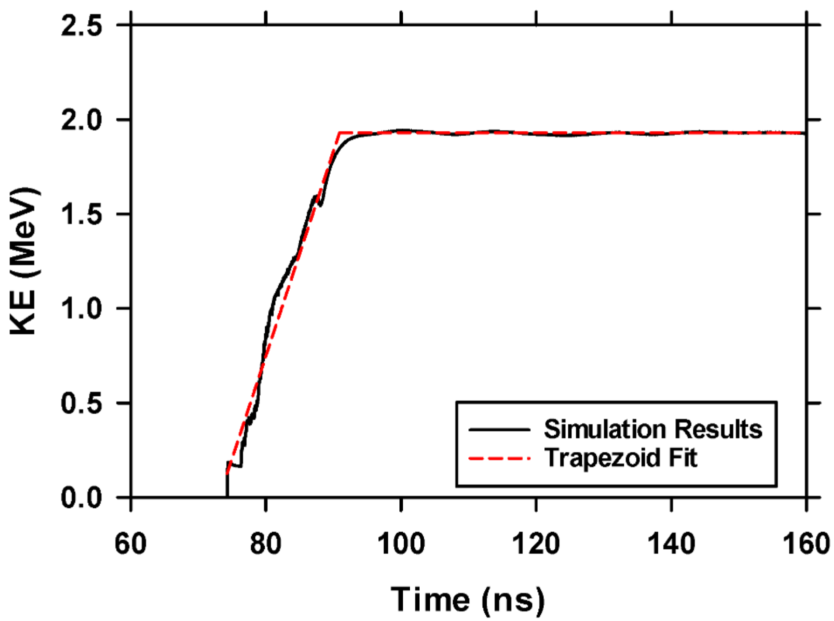
"Electron-beam corkscrew motion in an advanced linear induction accelerator", C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 49, Nov., 2021, pp 3548-3553

Scorpius

The energy variation on the current-pulse risetime can cause high-frequency corkscrew, which in turn can excite BBU.

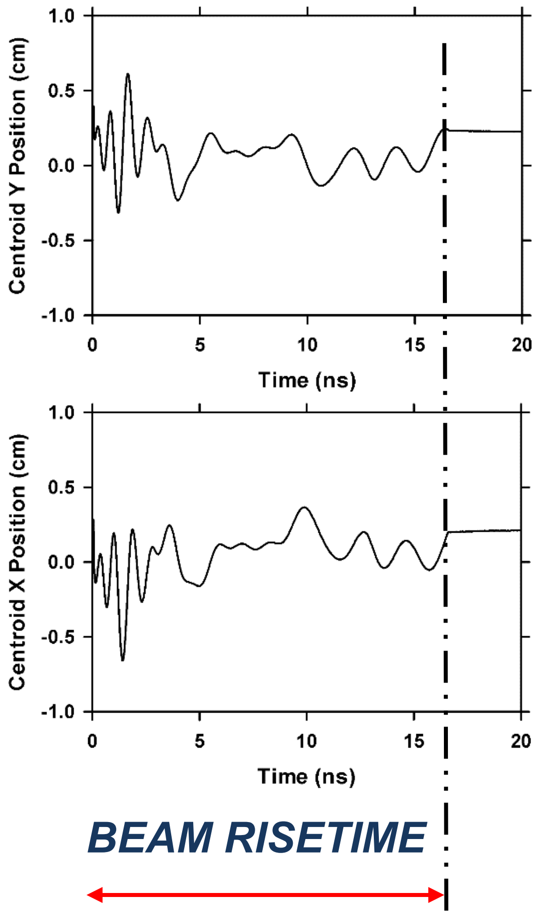
- **The injected current pulse has a 2-MeV energy ramp during the risetime that can cause corkscrew, even if injected on axis.**



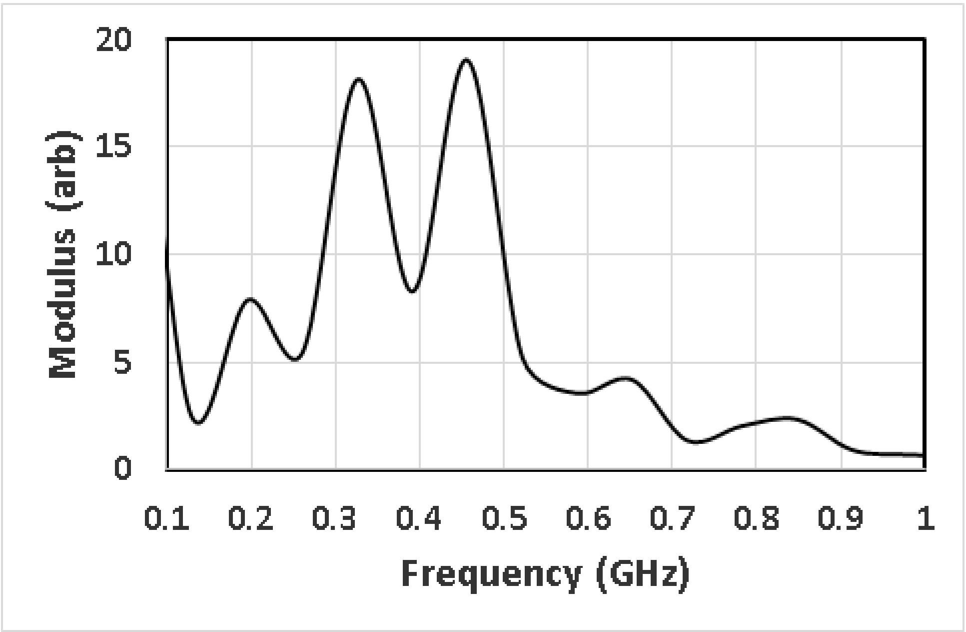


The fast risetime produces high-frequency corkscrew due to deflections by solenoid-misalignment dipoles.

Beam-Head Corkscrew



- The frequency of the beam-head corkscrew is in the range that can excite BBU.
- Expected to be most effective for exciting BBU in the lower-frequency resonance, near 220 MHz.



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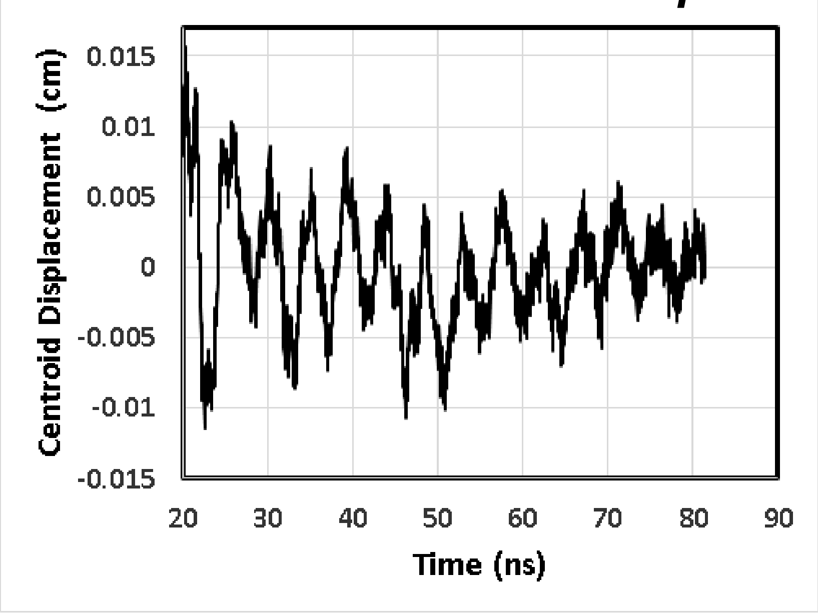
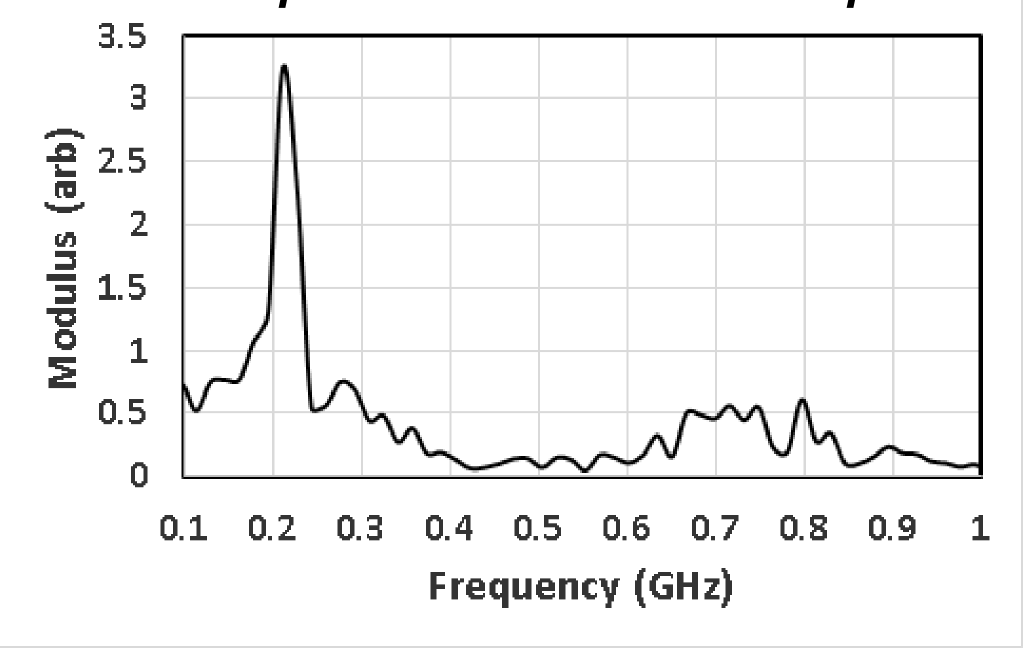
In the LAMDA simulations, the rise-time corkscrew excited the lowest frequency mode of BBU.

- Beam- head corkscrew frequencies (less than 500 MHz) are not very effective at exciting the virulent 670-MHz BBU mode.
- Peak-to-peak amplitude of BBU at LIA exit is less than about 0.2 mm.
  - Less than 7% envelope radius

BBU on current flattop

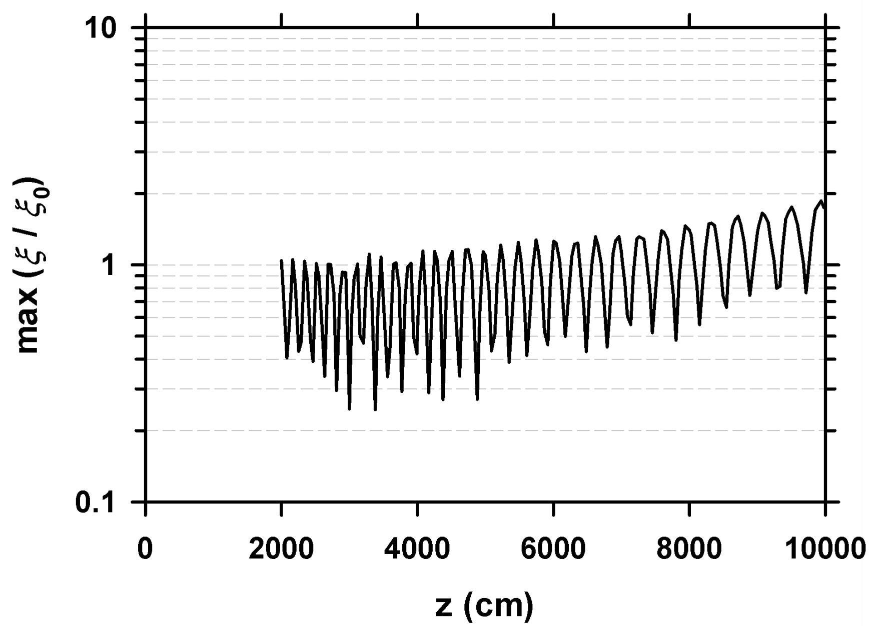


Spectrum of BBU on flattop

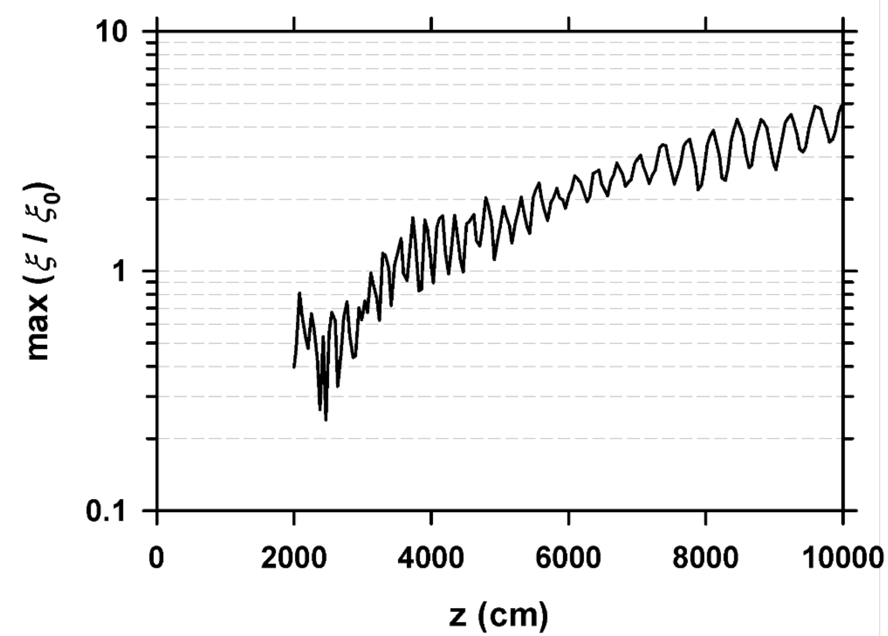


Beam-head corkscrew excited BBU grows more rapidly than BBU excited by the pulse risetime alone.

- BBU can be excited by corkscrew even if a centered beam is launched straight down the axis.
- Mitigation of beam-head corkscrew can diminish pulse-excitation of BBU.



Offset beam, no corkscrew



Centered beam, plus corkscrew

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(in review by TPS)

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Ion-Hose Instability

Scorpius is susceptible to ion-hose instability because of its long length and its high current.

- **Historically, the ion-hose instability was considered a danger for long-pulse, high-current electron LIAs like DARHT-II.**

- **However, ion hose is also a concern for multi-pulse LIAs.**

- **We have simulated this instability for the Scorpius multi-pulse LIA.**

- **The results for an early 72-cell Scorpius design have shown that the magnetic focusing field will be strong enough to suppress ion-hose instability if the residual gas pressure is below a value that is readily attainable with the present designs of accelerator components for Scorpius.**

The ion-hose instability is the result of beam ionization of residual gas in a poor vacuum.

- **The electron beam rapidly ionizes any residual gas.**
- **Low energy secondary electrons are repelled by the beam space-charge field, leaving a positive-ion channel.**
- **The positive-ion channel attracts the electron beam, which may be off center.**
- **The attraction between beam and channel causes them to oscillate about the center of mass.**
- **This oscillation is unstable, with a number of e-foldings proportional to ion density.**
- **Solved analytically for Gaussian beam and channel profiles with constant rms radii in uniform magnetic field[1] yields growth rate and most unstable frequency.**
- **Linear regime growth rate is proportional to ion density and is suppressed by magnetic focusing force.**

$$\max(\xi / \xi_0) = \exp\Gamma(z) : \quad \Gamma(z) \propto n_i z / B \propto f_e I_b z / B$$

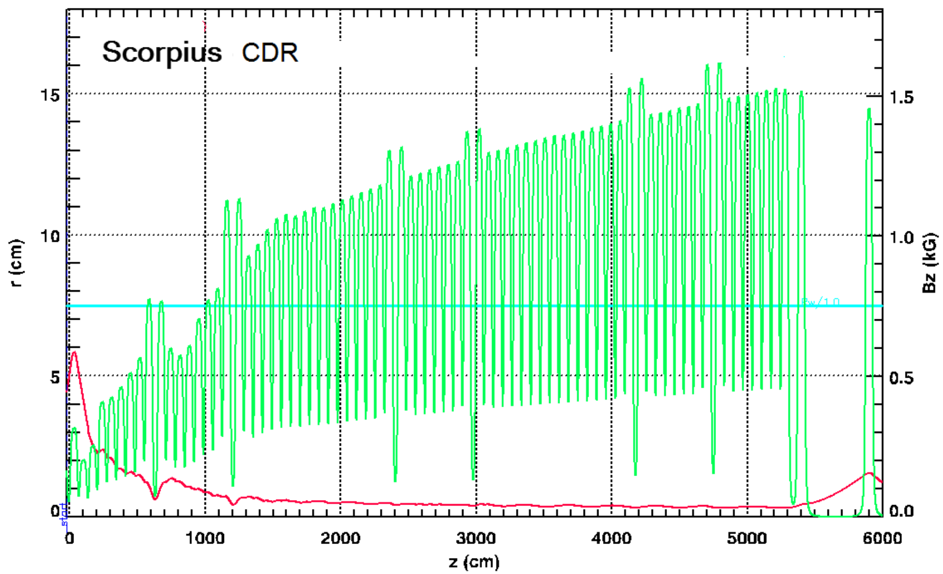
- **Frequency at maximum growth depends on beam size and current, and ion mass.**
- **Scaling validated experimentally with the ~2-kA, 2-μs-long pulse of the DARHT-II LIA[2].**

[1]T. C. Genoni and T. P. Hughes, *Phys. Rev. - ST Accel. Beams,* vol. 6, 2003.
[2]C. A. Ekdahl, et al., *IEEE Trans. Plasma Sci.,* vol. 34, 2006.

The Scorpius CDR magnetic tune for the 72-cell design transports a well-matched beam with no emittance growth evident in PIC code simulations.

A Magnetic Transport Tune for the Conceptual Design Report (CDR)

- The first cellblocks were used to focus the beam down to a small size to prevent emittance growth from accumulated spherical aberration of solenoids.
- The magnetic field in the first cell block is high enough to prevent the Image Displacement Instability (IDI).
- Magnetic field is high enough to suppress BBU, but without excessive magnet heating.
- Magnetic field increases approximately as $\sqrt{\gamma - \gamma_0}$ to minimize phase advance in order to reduce corkscrew motion.



Initial beam parameters:

- Injected Energy, KE_0 = 2.0 MeV
- Beam Current, I_b = 2.0 kA
- Initial envelope radius, r_0 = 4.95 cm
- Initial divergence, r_0' = 42 mr
- Normalized emittance, ε_n = 305 mm-mr

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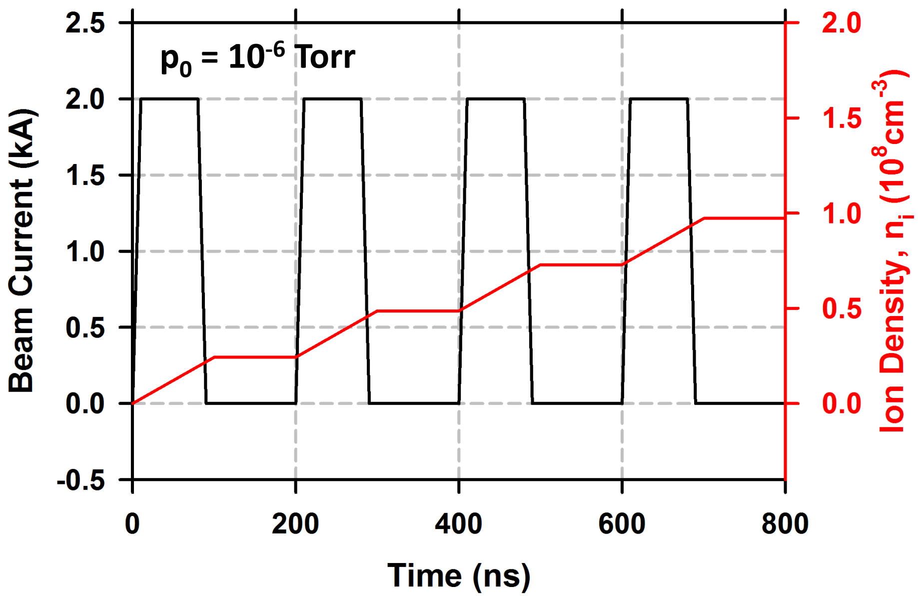
The ion-hose instability is also be a concern for multi-pulse, high-current linear induction accelerators (LIAs) due to persistence of the ion channel.



- For background pressures < 10^{-6} Torr, the ion channel persists and ion density increases during Scorpius pulse train (< 4 μs).
- Ion density increases linearly with time, $f_e = n_i / n_b = pt / \alpha = \text{Torr} \times \text{ns} / \alpha(\text{Torr-ns})$
- Growth rate is proportional to ion density, $\Gamma \propto \; n_i$ / B
- Frequency is inversely proportional to square root of ion mass.

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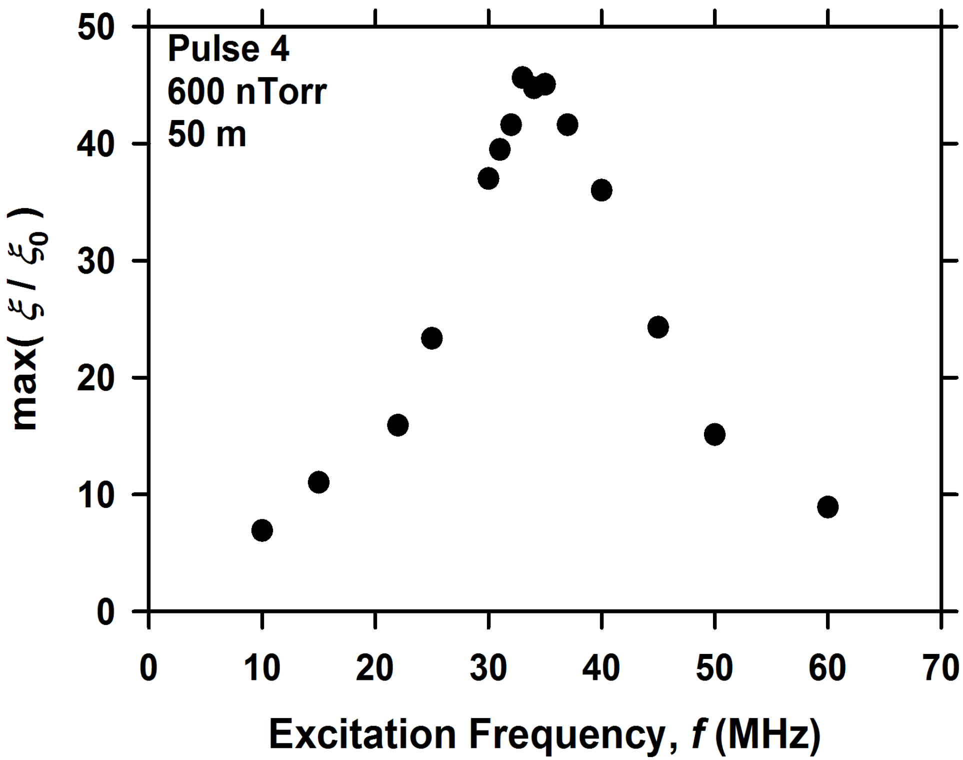
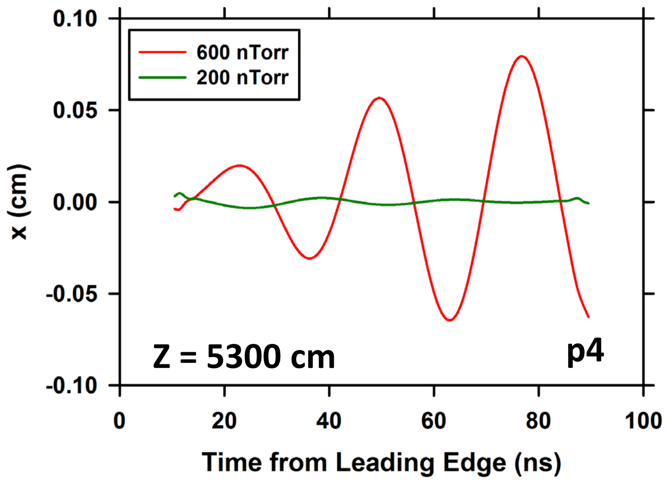
LAMDA simulations showed that the frequency of the ion-hose instability is high enough to blur the integrated radiographic source-spot.

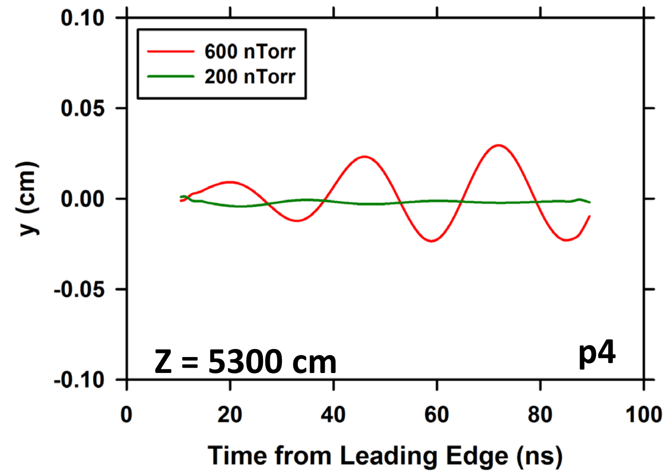
The most unstable frequency for H_2O in the nominal Scorpius tune is 34 MHz (~3 cycles on 90-ns pulse).



Each datum on this resonance curve for Pulse 4 is from a simulation with beam excited by a single frequency sine wave with amplitude 0.0071 cm.

Ion-hose amplitude would blur the radiographic source-spot of pulse-4 unless the residual gas pressure is less than ~200 nTorr (step offset injection).

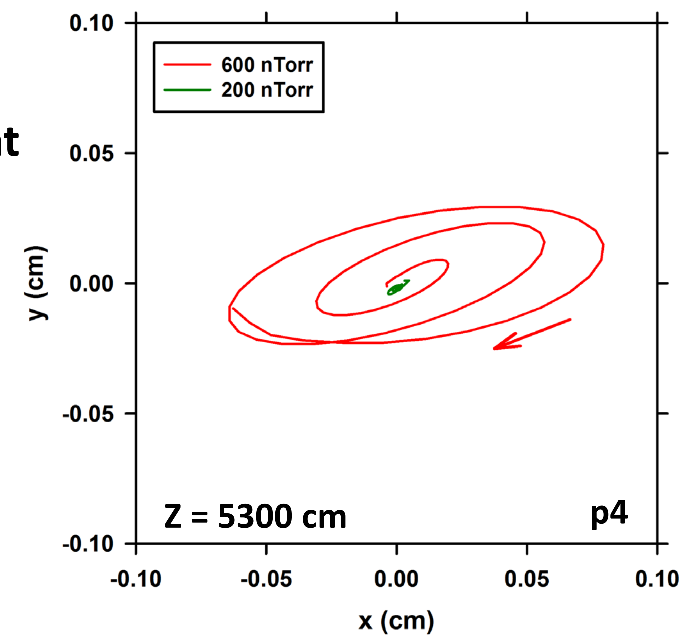




Blur of a matched beam at 53 m with 600 nTorr H_2O:

Beam R_{rms} < 0.3 cm

δx ~ 23% of R_{rms}
δy ~ 8% of R_{rms}



Only the 34-MHz fastest growing frequency is evident at the LIA exit, even though the initial step offset excites all frequencies.

"The ion-hose instability in a high-current, multi-pulse linear induction accelerator," C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 47, Jan., 2019, pp 300-306

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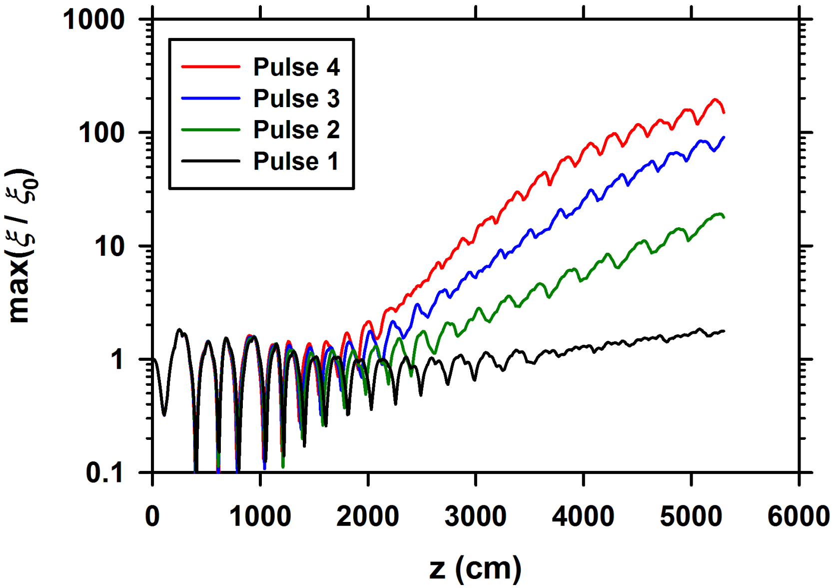
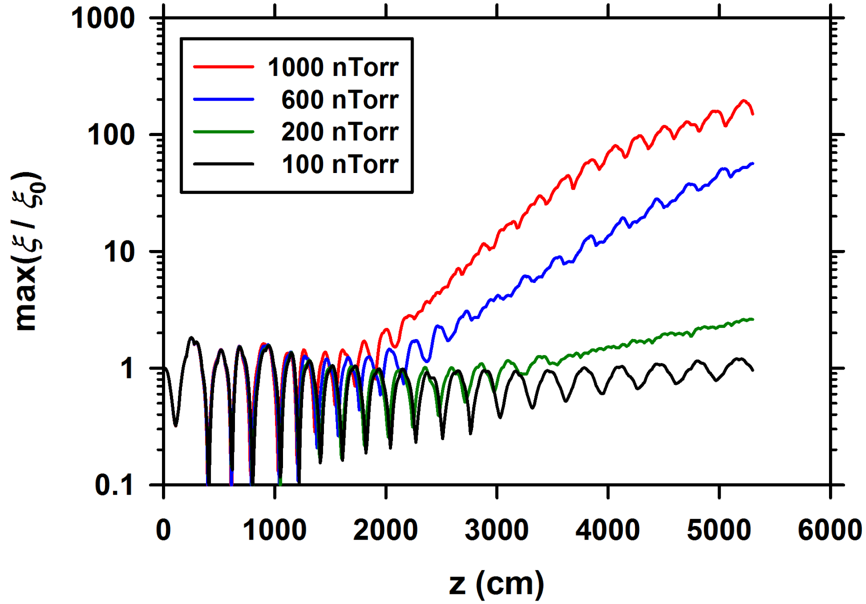
Maximum growth occurs when excited with 34-MHz sinusoid ("numerical tickler").

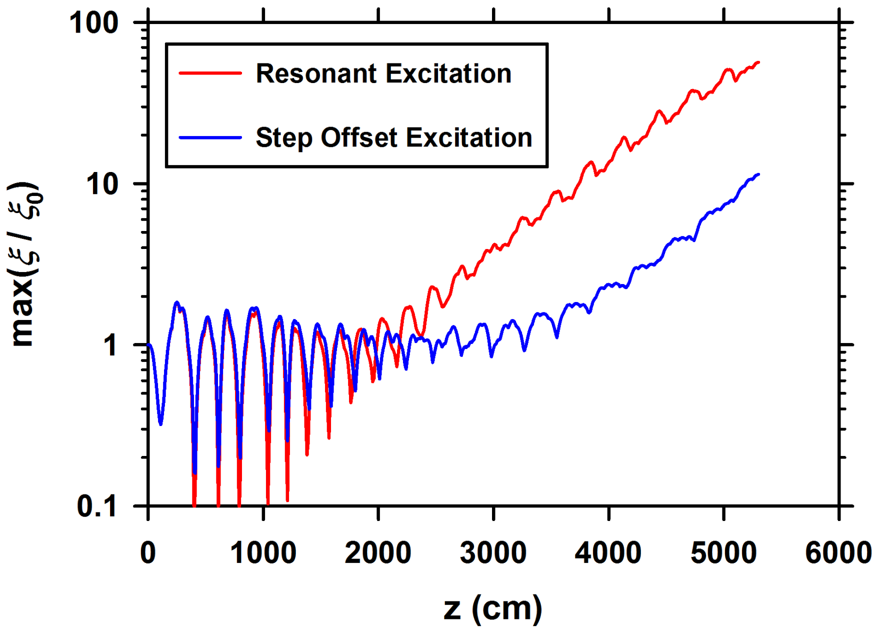


- Ion-hose instability in 50-m long LIA
- Scorpius CDR magnetic tune
- Residual gas = 1.0 μTorr H_2O
- Excited at maximum growth:
  - 34-MHz sinusoid
  - 0.0071-cm amplitude
- Envelope oscillations due to slight mismatch from current neutralization

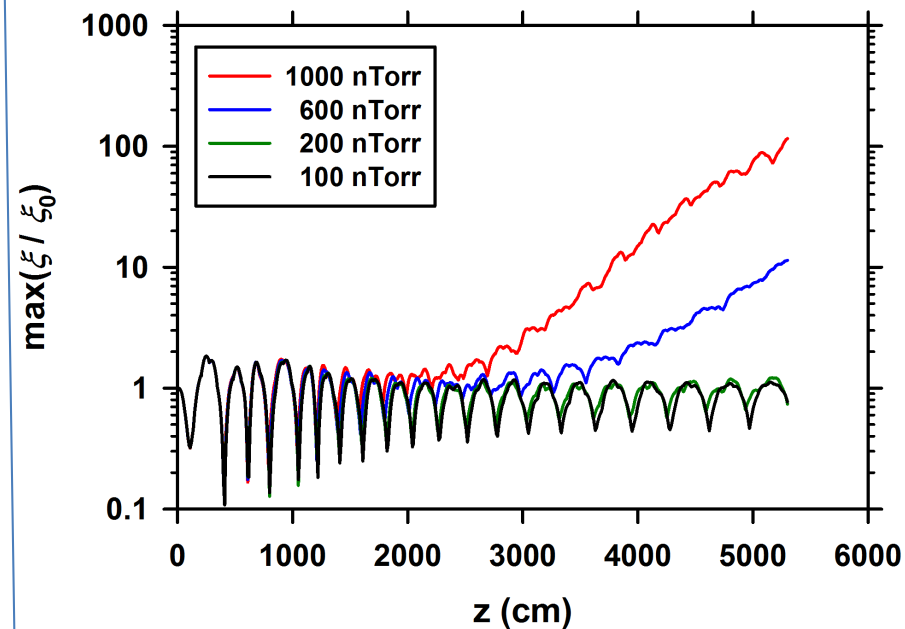


- Pulse 4 in Scorpius CDR tune, L= 50 m
- Residual gas = H_2O;
  - pressure = 100 nTorr to 1 μTorr
- Excited at maximum growth:
  - 34-MHz sinusoid
  - 0.0071-cm amplitude.

Using an initial condition relevant to pulse 4, injection of a constant-current beam offset from channel, caused a delay in the onset of exponential growth.



- Pulse 4 in Scorpius CDR magnetic tune
- 600-nTorr residual H_2O
- 0.0071-cm step-offset injection delays onset of exponential growth
- Reduces final amplitude by factor of 6.



- Pulse 4 in Scorpius CDR tune
- 0.0071-cm step offset injection
- Varied H_2O residual pressures
- No growth for $p < 200$ nTorr in 72-cell LIA

"The ion-hose instability in a high-current, multi-pulse linear induction accelerator," C. Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 47, Jan., 2019, pp 300-306

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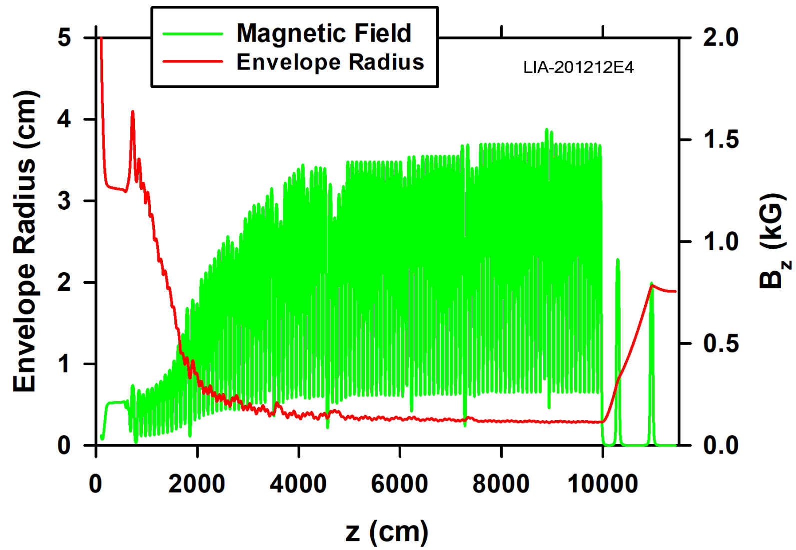
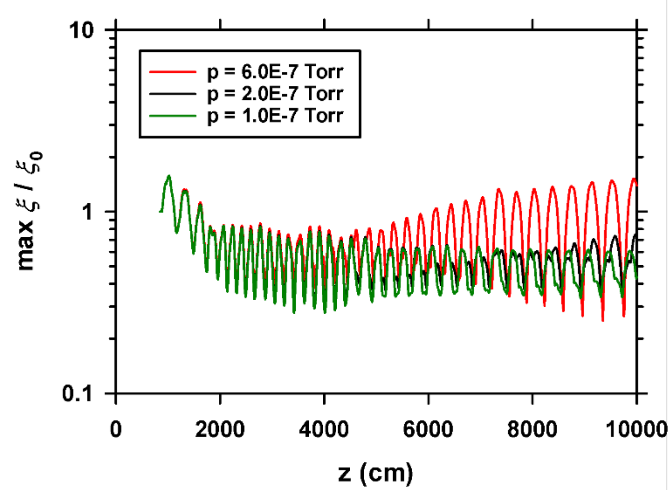
LAMDA simulations of ion-hose with the 102-cell Scorpius lattice used for this evaluation showed no amplification during the last pulse for p < 200 nTorr.

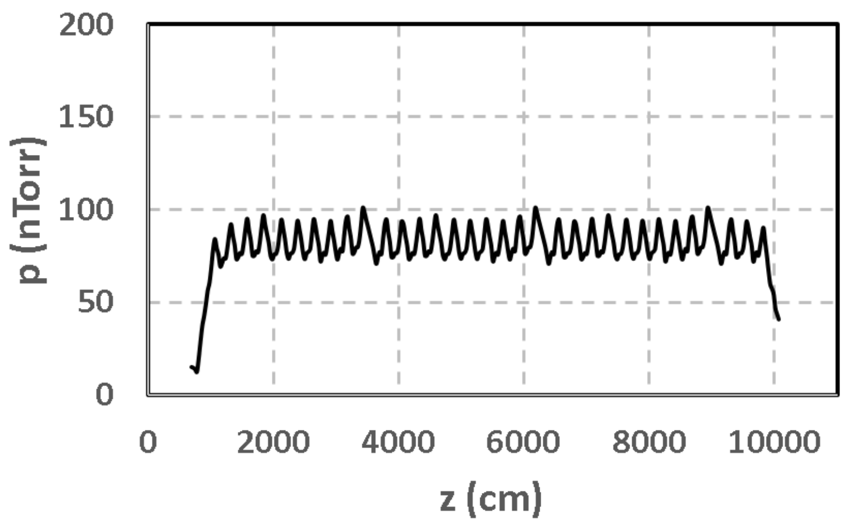
- The same nominal tune was used with a uniform pressure distribution.
- Current pulse was trapezoidal:
  - 10-ns rise
  - 60-ns flattop, 1.45 kA
  - 10-ns fall
- Simulations did not take into account any increase in ion background due to beam-head/tail scraping.





The ion-hose growth in the Scorpius final design will be simulated using a recent calculation of the expected residual pressure.

- The residual pressure in the LIA was simulated by Ryan Holguin using MolFlow+.
- Most recent LIA lattice was used for this simulation.
- Heather Andrews provided experimental data for this simulation.
- The simulation indicates that a residual pressure can be achieved that is one-half the 200-nTorr limit.
- Although the pressure is periodic, parametric interaction with ion-hose is unlikely because the periodicity is three times too great to resonate.
- LAMDA simulations are in progress.



Engineered Mitigation of the Resistive Wall Instability

Scorpius is susceptible to the resistive wall instability, because of its high current and the long drift regions in the DST where there is no magnetic field.

- **The electron beam is attracted to the beam tube wall by its image charge, and repelled from the wall by its image current.**
- **For a relativistic beam, this results in a net attraction to the wall.**
  - **Attraction to wall = bare electrostatic force / γ^2 => a weak force for relativistic beam**
  - **This attraction to the wall is easily counteracted by magnetic focusing**
- **Instability results from magnetic field diffusion into wall, reducing the magnetic repulsion of the beam tail, causing a gradual head-to-tail sweep toward the wall as the beam propagates[1].**
- **A characteristic length for significant growth in a magnetic guide field has been inferred from theory[2] ;**

$$z_g \approx 5.6 \frac{B_{kG} b_{cm}^3}{I_{kA}\sqrt{\rho_{\mu\Omega-cm}\tau_{\mu s}}} \text{ meters}$$

- **Instability growth rate at any point in a beam pulse depends on all of the preceding beam current, including that of preceding pulses.**
- **This pulse-to-pulse coupling can be simulated with our LAMDA beam dynamics code[3].**

[1] Bodner, Neil, and Smith, *Particle Accelerators* 1, (1970) pp. 327 - 334
[2] Caporaso, Barletta, and Neil, *Particle Accelerators* 11, (1980) pp. 71 – 79
[3] Ekdahl, *IEEE Trans. Plasma Sci.* 45, (2017) pp. 811 - 818

The characteristic signature of resistive-wall instability is a head-to-tail sweep toward the wall.

<u>Illustrative Example</u>

Beam Pipe:

- **6" diameter**
- **St. St. (~78 μΩ-cm)**

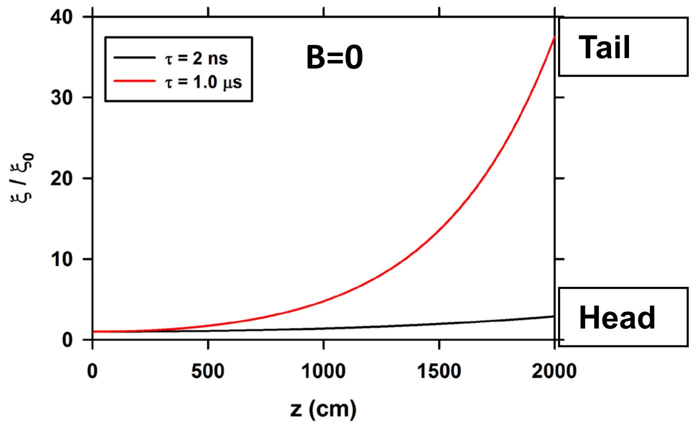
Beam Parameters:

- **Current = 2 kA**
- **Energy = 10 MeV**
- **Pulse = 1 μs**

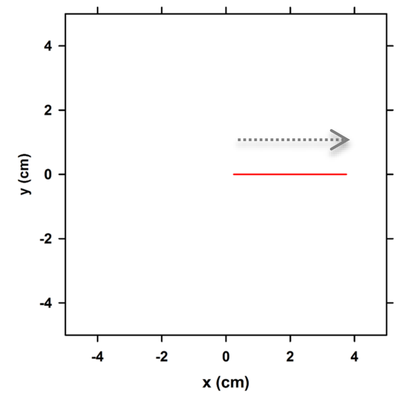
Centroid Motion:

- **ξ : displacement from axis**
- **ξ_0 = 1 mm**

Displacement of pulse head and tail vs axial distance in pipe

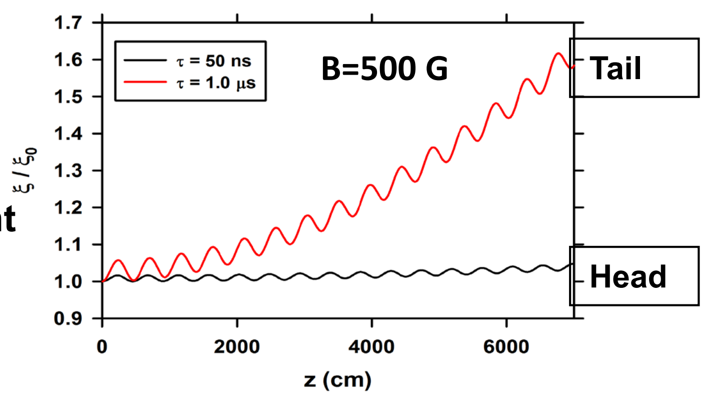


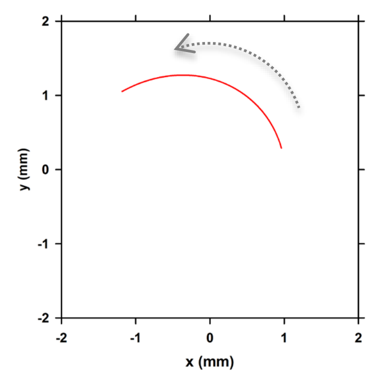
Trajectory at exit



Beam tail sweeps ~4 cm in 20 m

Axial magnetic field suppresses instability, and converts motion to azimuthal E x B drift.





Beam tail sweeps ~ <u>0.6 mm</u> in <u>70 m</u>

"The resistive-wall instability in multi-pulse linear induction accelerators," *IEEE Trans. Plasma Sci.*, May, 2017

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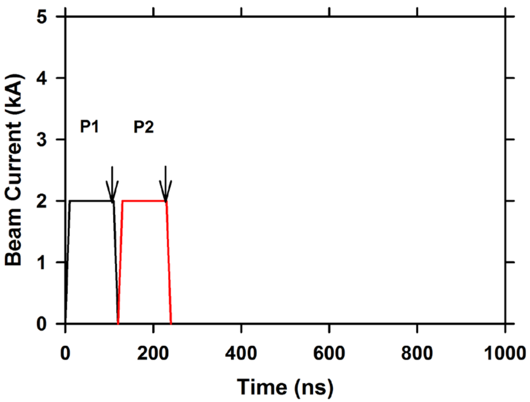
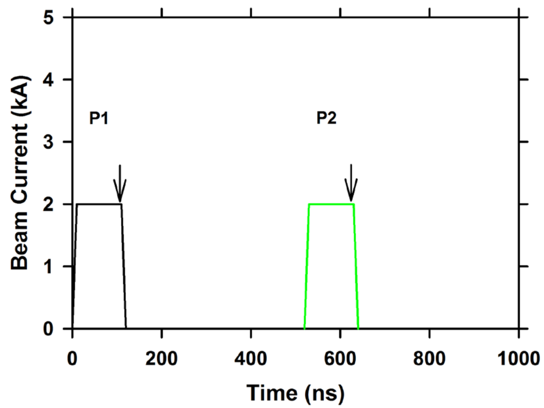
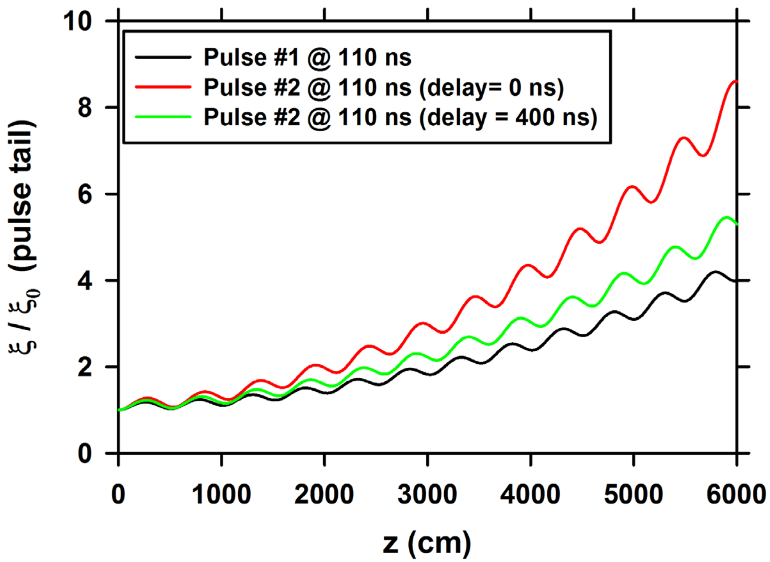
Pulse-to-pulse coupling of the resistive-wall instability causes a spread in the source spot positions.







Illustrative Example

Beam Pipe:
- **3” diameter**
- **St. St. (~78 $\mu\Omega$-cm)**

Transport Parameters:
- **B_z = 500 G**

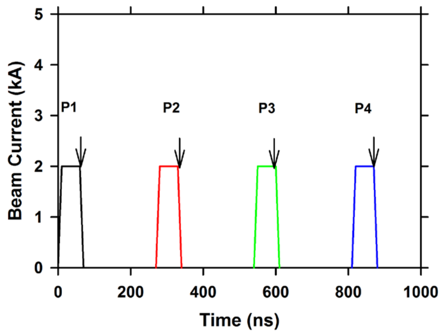
Beam Parameters:
- **Current = 2 kA**
- **Energy = 10 MeV**
- **Pulses = 100 ns**

Coupling is strongest for shortest inter-pulse spacing

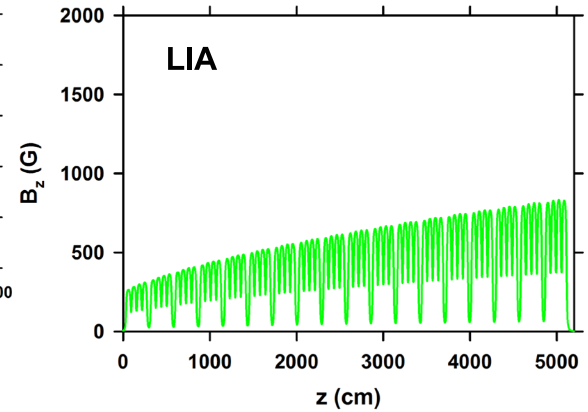
“The resistive-wall instability in multi-pulse linear induction accelerators,” *IEEE Trans. Plasma Sci.*, May, 2017

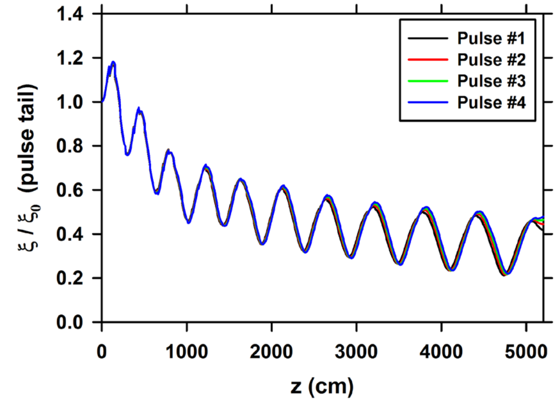
LAMDA simulations show that the magnetic field needed to suppress BBU is enough to suppress resistive-wall coupling of pulses in the LIA.

However, downstream transport to final focus could be troublesome.



Low-field tune (only suppresses BBU to ~6 e-foldings)





Focusing field attenuates instability and minimizes coupling

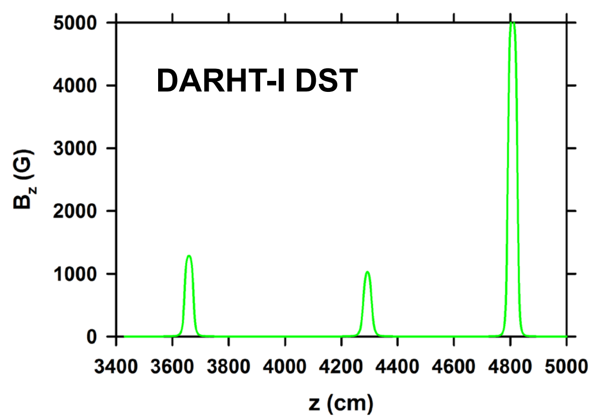
- Input parameters:
- (Scorpius-like)

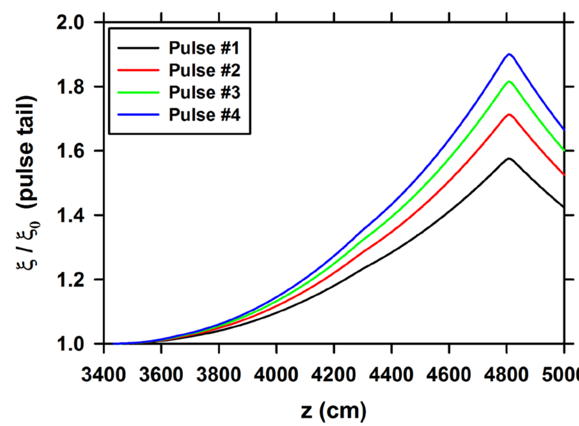
- 4 pulses
- 2-kA
- 10-ns rise and fall
- 50-ns flattop
- 200-ns separation

- 2-Mev injected to LIA
- 0.25-MeV / cell for 72

- 20-Mev injected to DST

The 14-m DARHT-I DST is similar to the Scorpius DST





Coupling produces spot blur and spread at focus !

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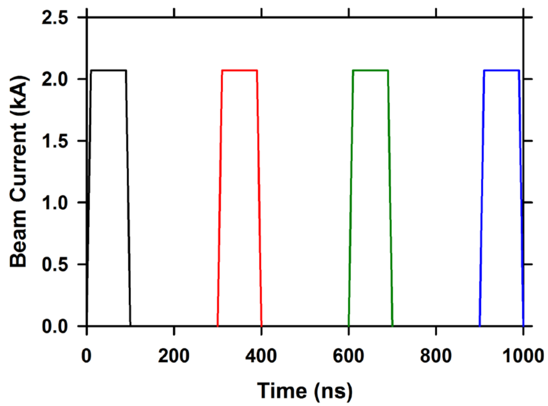
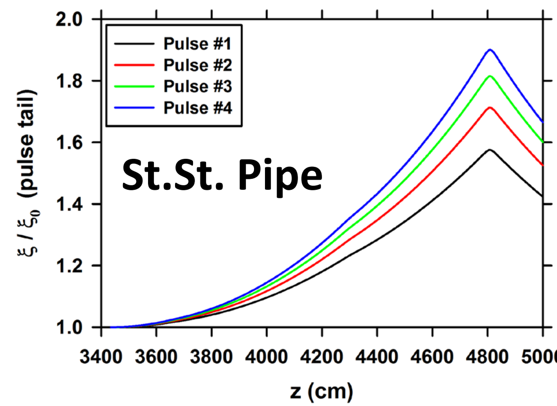
The Scorpius focusing field is strong enough to suppress the resistive-wall instability in the LIA, and high-conductivity beam pipe can reduce it in the DST.

- **Scorpius CDR focusing field is strong enough to suppress instability in the LIA.**
- **Instability can be mitigated in Scorpius downstream by use of aluminum beam pipe.**

Pulse format:
- **Flattop = 80 ns**
- **Rise, Fall = 10 ns**
- **Interpulse = 200 ns**

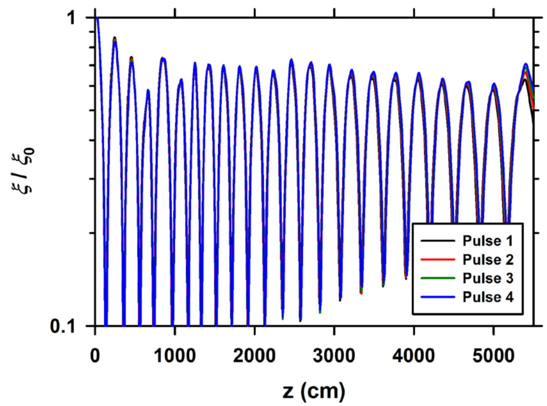


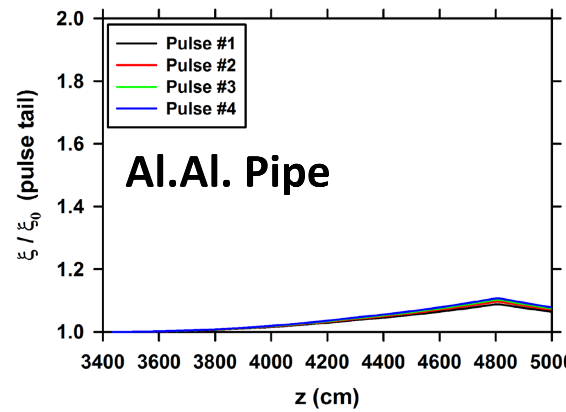
DARHT-I Downstream Example:



Coupling produces spot blur and spread at focus !

Magnetic field suppresses instability in LIA.





High conductivity beam pipe mitigates instability

"The resistive-wall instability in multi-pulse linear induction accelerators," Carl Ekdahl, *IEEE Trans. Plasma Sci.*, vol. 45, no. 5, (2017) pp. 811 -818

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Many engineers and scientists across the NNSA complex have contributed to this evaluation of beam stability. In particular, much credit is owed to :

- **Lawrence Livermore National Laboratory**
  - Yu-Jiuan Chen, Eric Clark, Nate Pogue, Will Stem, Katherine Velas
- **Sandia National Laboratories**
  - Michael Mazarakis, Matt Sceiford
- **Mission Support and Technical Services**
  - Trevor Burris-Mog, Evan Scott, Michael Weller
- **Los Alamos National Laboratory**
  - Sergey Kurennoy, Rodney McCrady, Derek Neben
  - Heather Andrews, Barry Gardner, Ryan Holguin

(My sincere apologies to all those I've left off of this list)

To summarize this evaluation of beam dynamics concerns for Scorpius;

- **So far, we have found no insurmountable impediment to producing a radiographic-quality electron beam with the Scorpius design.**
- **Of course, the results of this evaluation must eventually be checked for as-built dimensions of the injector, LIA, and DST, with a relevant magnetic tune, as has often been done for DARHT.**

Questions?

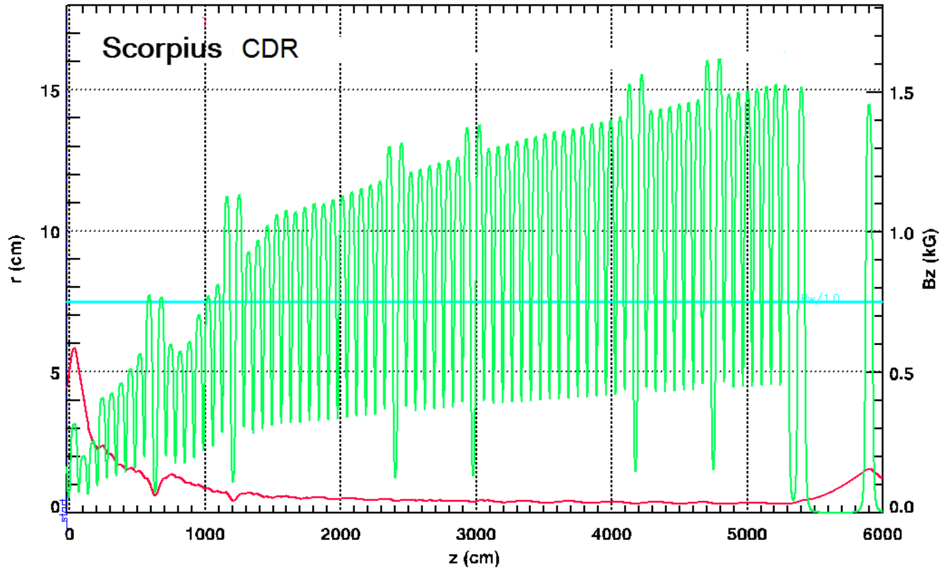
Additional Information

- BBU (pulse risetime impact)
- IDI for 102 cells
- Ion-Hose channel physics
- ITS tickler BBU measurements

The Scorpius magnetic-field transports a well-matched beam with no emittance growth evident in PIC code simulation results.

A Magnetic Transport Tune for the Conceptual Design Report (CDR)

- The first cellblocks were used to focus the beam down to a small size to prevent emittance growth from accumulated spherical aberration of solenoids.
- The magnetic field in the first cell block is high enough to prevent the Image Displacement Instability (IDI).
- Magnetic field is high enough to suppress BBU, but without excessive magnet heating.
- Magnetic field increases approximately as $\sqrt{\gamma - \gamma_0}$ to minimize phase advance in order to reduce corkscrew motion.



Initial beam parameters:

- Injected Energy, KE_0 = 2.0 MeV
- Beam Current, I_b = 2.0 kA
- Initial envelope radius, r_0 = 4.95 cm
- Initial divergence, r_0' = 42 mr
- Normalized emittance, ε_n = 305 mm-mr

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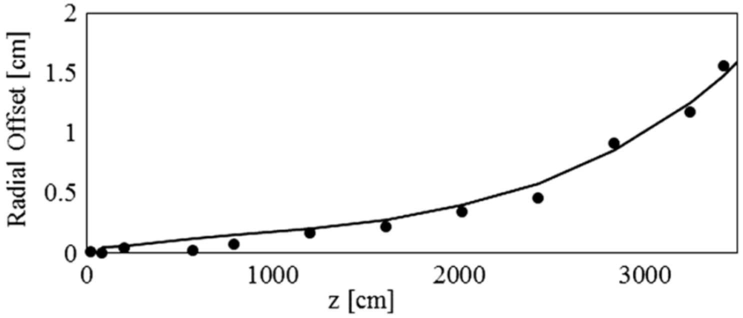
Image-Displacement Instability (IDI)

Scorpius is susceptible to the image-displacement instability (IDI) because of its high current and periodic gaps.

- The electron beam is attracted to the beam tube wall by its image charge, and repelled by its image current. For a relativistic beam, this results in a net attraction to the wall = bare electrostatic force / γ^2, which is easily counteracted by magnetic focusing.
- However, image and focusing forces become unbalanced at a cavity gap:
  - Image charge accumulates at corners, strengthening the attractive force.
  - Image current is diverted to outer wall of cavity, weakening repulsive force.
  - Result is a deflection toward wall.

Comparison of XTR simulation of IDI simulation (solid line) and data from DARHT-I BPMs (dots)
(from T. J. Burris-Mog, etal., *Phys. Rev. Accel. Beams*, 2017)



- For gaps with width *w* separated by a distance *L* in tube with radius *b*, the instability is suppressed by uniform *B* if

$$B_{kG}^2 > 1.36\beta\gamma I_{kA} w_{cm} / (b_{cm}^2 L_{cm})$$

- For example, a 1.4-kA, 4-MeV beam with Scorpius gaps only needs $\langle B \rangle >$ ~90 G.
- Average focusing in Scorpius LIA is initially > 90 G.

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Ion-Hose channel expansion

Thermal expansion of channel is too slow to reduce plasma density between pulses.

- **Channel initially heated to** $T = S_{col} J \delta t / C_V$ **(units: K, MeV/(g/cm2), kA/cm2, ns, J/g-K)**
- **Ion density on axis of expanding channel (initially uniform with radius *a*) is[1]:**

$$n_i(t)/n_{i0} = 1 - \exp\left(-t_a^2 / t^2\right)$$

where

$$t_a = a / v_\theta; \quad v_\theta = \sqrt{2kT_i / m_i}$$

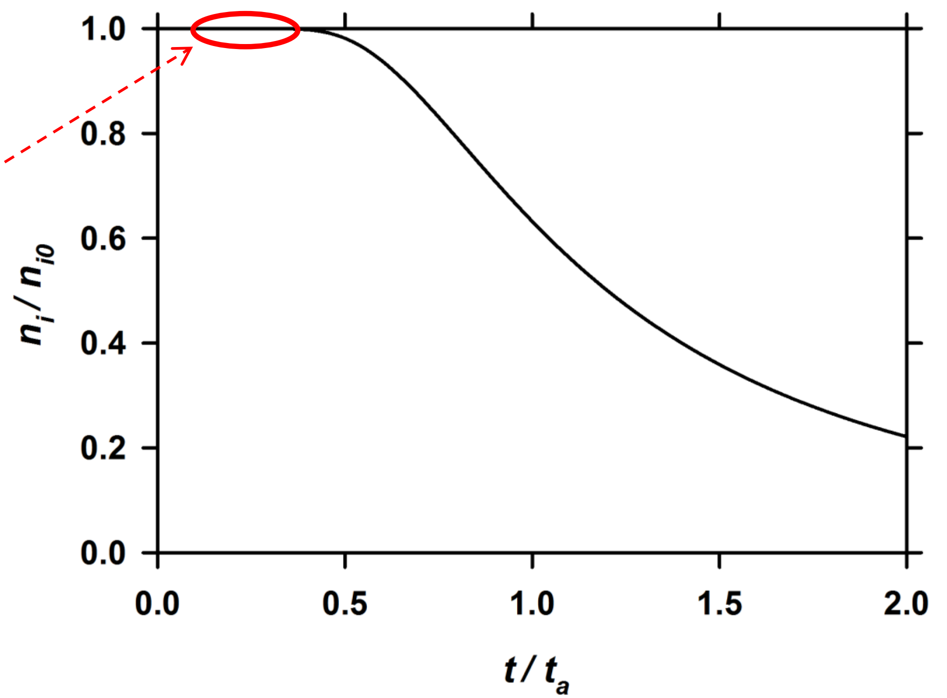
After Pulse 3 at Scorpius LIA exit :

- **R_b = a = 0.35 cm**

For water vapor:

- **T = 1600K = 0.14eV**
- **v_{th} = 0.12 cm/μs**
- **t_a = 2.9 μs**
- **t_i < 1μs**
- **t_i/t_a<0.35**

=> n_i/n_{i0} > 0.9999 at start of Pulse 4



[1]P. Molmud, *Phys. Fluids*, vol. 3, no. 3, pp. 362 - 366, 1960

Recombination is too slow to reduce plasma density between pulses.

- **Radiative recombination rate[1]:**

$$R_r = 5.2\times10^{-14}\left(\chi/kT\right)^{1/2}\times\left[0.429+0.5\ln\left(\chi/kT\right)+0.469\left(\chi/kT\right)^{-1/3}\right]\ \mathrm{cm}^3/\mathrm{s}$$

- **3-body collisional recombination rate[1]:**

$$R_c = 1.4\times10^{-31} n_i N_{cl}^6\left(\chi/kT\right)^2\times\exp\left[\chi/\left(N_{cl}+1\right)^2 kT\right]\quad \mathrm{cm}^3/\mathrm{s}$$

$$N_{cl} = 126 Z^{14/17} n_i^{-2/17}\left(\chi/kT\right)^{-1/17}\times\exp\left[4\chi/17 N_{cl}^3 kT\right]$$

Parameter	Symbol	Unit	Value
Ion density	n_i	cm^{-3}	$<3\times10^8$
Ion Temperature	kT	eV	0.14
Collisional Rate	R_c	cm^3/s	8.5×10^{-13}
Collisional Time	t_c	s	**3,915**
Radiative Rate	R_r	cm^3/s	1.4×10^{-12}
Radiative Time	t_r	s	**2,307**

[1]**R. C. Elton, in *Methods of Experimental Physics, vol. 9A, Plasma Physics*, H. R. Griem and R. Lovberg, Ed., 1970, Academic Press, pp. 115 - 168.**

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Between pulses, the ion channel is neutralized by secondaries confined by the solenoidal magnetic field.

- **The beam ionizes the residual background gas, and secondary electrons are ejected from the channel.**
- **Secondary "cloud" outside of the beam is subject to radial E-field from the beam space-charge and axial B-field from the solenoid.**
- **Secondary electrons rotate with E X B drift velocity, $r\omega_D = E/B$**
- **According to theory of crossed-field confinement of a non-neutral plasma, secondary electrons are confined if axial B-field is strong enough.**
  - **eg., if Hull cutoff for magnetic confinement is satisfied**

$$\omega_{ce} > 2\frac{c}{R_W}\frac{1}{1-\left(R_{env}/R_W\right)^2}\left[2\frac{e\phi_{sc}}{mc^2}+\left(\frac{e\phi_{sc}}{mc^2}\right)^2\right]^{1/2}$$

$$e\phi_{sc} \approx 60 I_b\left(1-f_e\right)\ln\left(R_W/R_{env}\right)$$

  - **For Scorpius tune, this is satisfied on average through most of the LIA**
- **After beam passes, secondaries implode to neutralize the ion channel.**

∴ **Between pulses there is little, if any, electrostatic channel expansion.**

Diochotron Instability

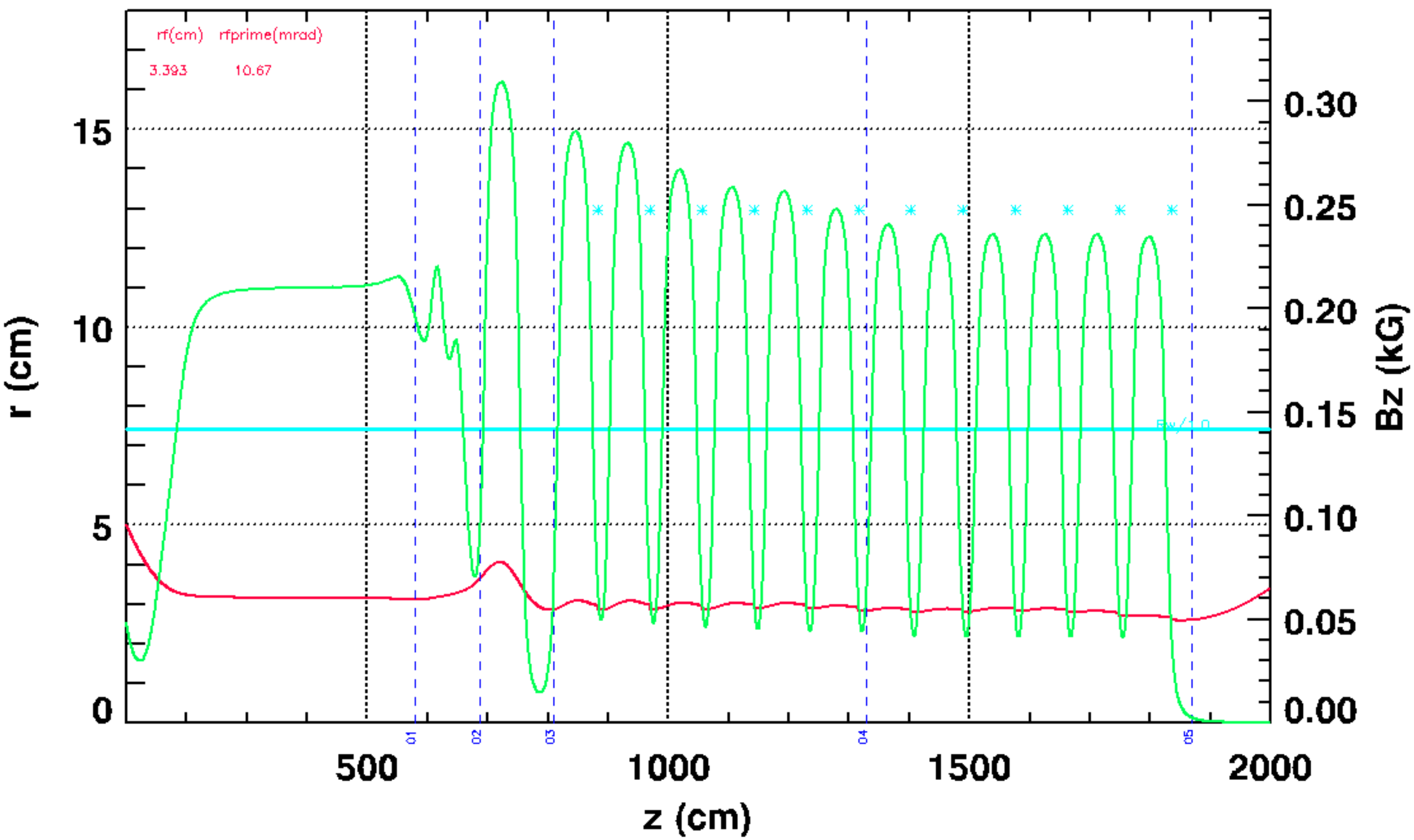
The diocotron instability can be a problem for shielded-cathode diodes, as on DARHT, FXR, and Scorpius. (Under investigation)

- **Sheared rotational velocity can cause an interchange type instability if density profile has an off axis maximum (concave profile).**
- **Theoretically shown to be stable for convex beam profile.**
- **Classical theory pertains to slow rotation mode in uniform axial field resulting from space-charge E X B**
  - **Characterized by strength parameter:** $s \equiv \omega_p^2 / \omega_c^2 = \gamma n_e m_e / \varepsilon_0 B^2$
  - **S ≈ 1 in magnetrons, s << 1 for most diochotron theory in literature**
  - **Growth rate is proportional to diochotron frequency** $\omega = \omega_D \eta; \quad \omega_D \equiv \omega_p^2 / \omega_c$
  - **η is shape factor characterizing the concavity of the current profile.**
- **The beam from a shielded-cathode diode rotates due to conservation of canonical angular momentum as it enters the focusing B-field in the anode.**
- **The beam can be hollowed out by edge focusing due to nonlinear fields:**
  - **Bz of solenoids and Er of cathode entrance (spherical aberrations)**

- **It follows that Scorpius beam can be diochotron unstable.**
- **Under investigation by Eric Clark (LLNL) with WARP PIC simulations.**

Using ITS to Validate BBU Predictions with an Electron Beam

The ITS can test transport and beam stability using 12 Scorpius cells.



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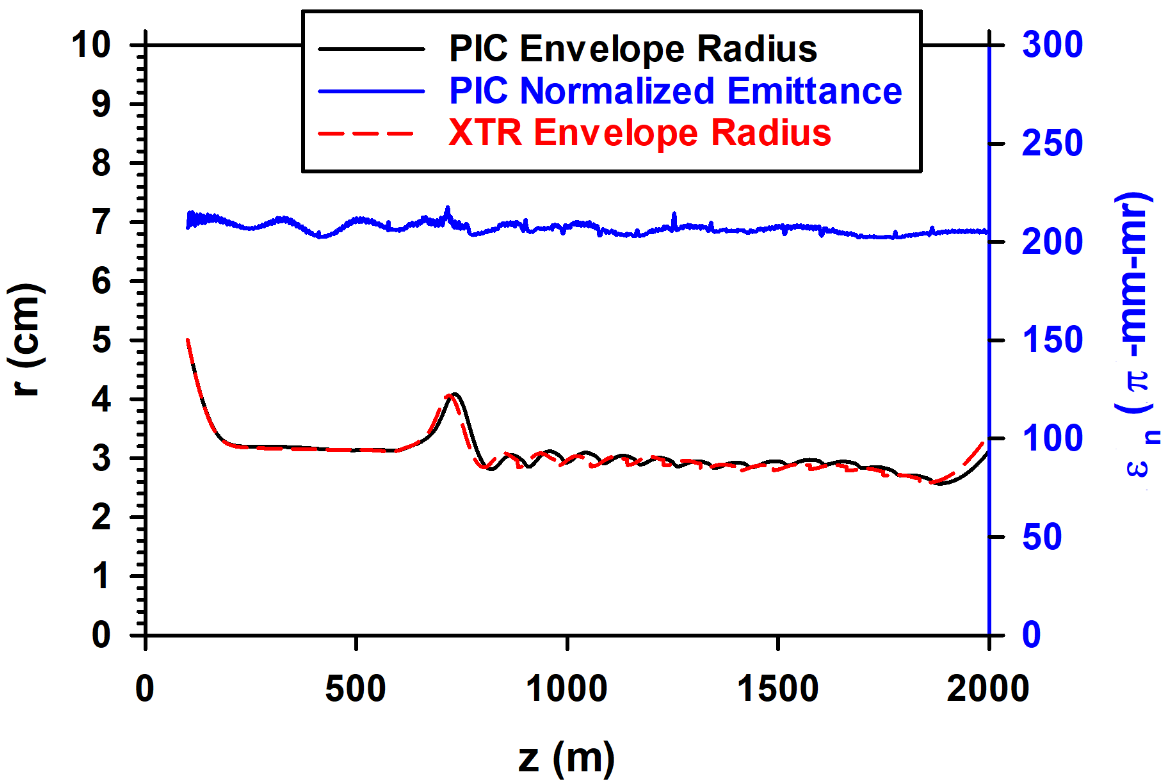
A nominal tune for ITS transports a stable envelope with no emittance growth.

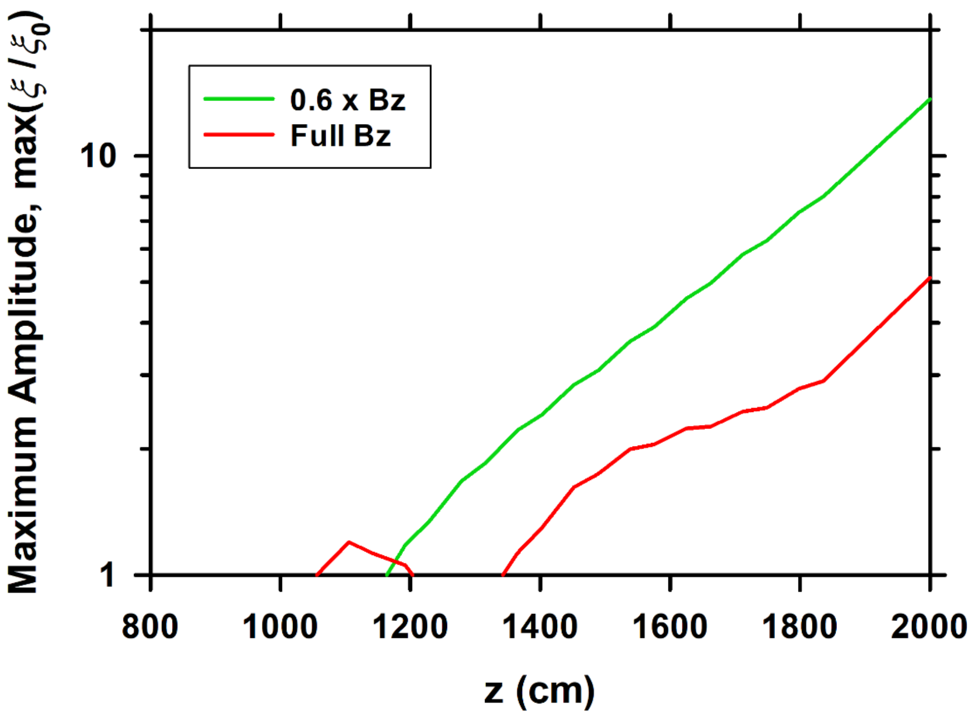
- Envelope stability and associated emittance growth was assessed using LSP-Slice PIC code simulations.
- Envelope code and PIC code results are in agreement when both are launched at the handoff location with the same initial conditions.



Scorpius

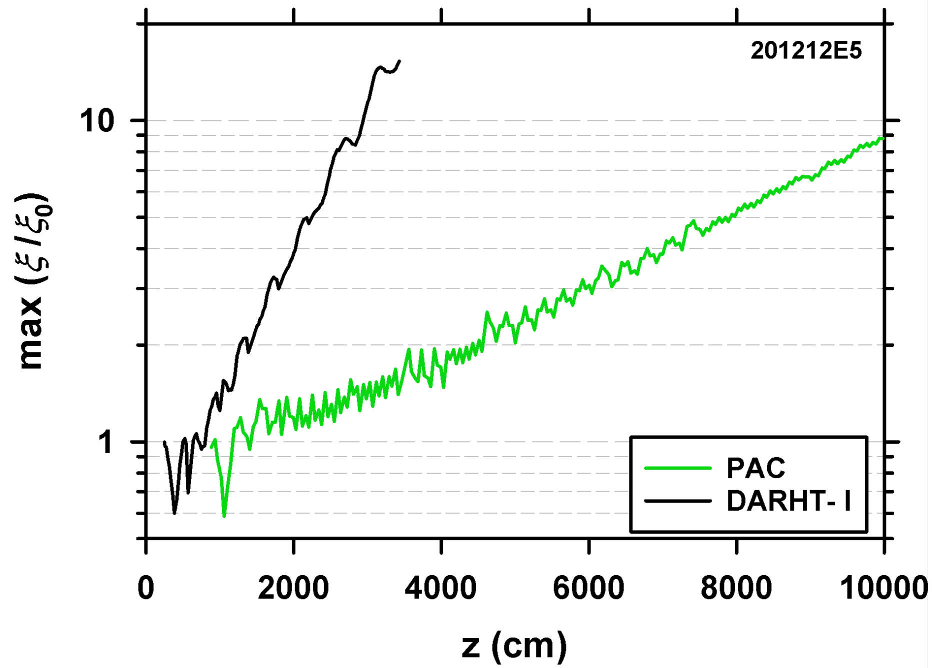
This ITS tune is suitable for BBU measurements.

If the BBU gain is insufficient for a high fidelity measurement, the field can be substantially lowered, and still be high enough to stabilize the image displacement instability.



BBU growth for PAC was calculated to be less than in DARHT-I.

- BBU growth in DARHT-I is reduced by natural stagger tuning due to asymmetric transverse impedance and Larmor rotation of beam.
- Scorpius prototype accelerator cell (PAC) has symmetric impedance.
- Both calculations used impedance model fitted to experimental measurements of transverse impedance.
- Both calculations were resonantly excited at the peak impedances (worst case).



(published by TPS, 2020 & 2021)